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Wireless Sensor Networks

Design, Deployment and Applications

Edited by Siva S. Yellampalli

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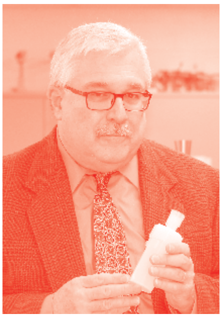

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Meet the editor

Dr. Siva Yellampalli is a Professor of Practice in the School of Engineering and Sciences, SRM University, Andhra Pradesh, India. He obtained his MS and Ph.D. from Louisiana State University, USA. His research focuses on system-level design for power optimization. His area of research encompasses different fields such as very-large-scale integration (VLSI), mixed-signal circuits/system development, the Internet of Things (IoT), and sensors. He published a book in the area of mixed-signal design and edited two books on carbon nanotubes and one book on micro-electro-mechanical system (MEMS) sensors. Dr. Yellampalli has also published more than 100 international journal papers and Institute of Electrical and Electronics Engineers (IEEE) conference papers. He has also delivered keynote speeches at international conferences in Canada, Dubai, and Spain including tutorials at various IEEE International conferences. He has been a consultant to various semiconductor companies.

Contents

Preface

Wireless sensor networks (WSNs) are new wireless networks used in numerous applications to sense and monitor various physical and environmental parameters. This adaptation is made possible by the advances made in semiconductors, networking, and material science technologies. Due to these advancements, WSNs are being adapted into various applications such as military sensing, physical security, air traffic control, traffic surveillance, video surveillance, and more.

This book focuses on understanding the design, deployment, and applications of WSNs. The book is divided into three sections. Section 1 provides an overview of WSNs and their various applications. Section 2 focuses on various design and deployment techniques and challenges. Section 3 discusses some specialized applications and challenges in adapting WSNs for different purposes.

Section I: Overview

Chapter 1: Wireless Sensor Networks: Applications

This chapter presents an overview of WSNs. It describes in detail various components of WSNs and their main characteristics. The chapter also gives an overview of the various WSN architectures along with the characteristics to optimize when designing a WSN for various applications.

Chapter 2: Wireless Sensor Networks: Applications and Challenges

This chapter discusses issues of WSNs ranging from applications to challenges. It examines various features such as signal processing techniques, topology, approaches, and others, which that are needed for WSN design. The chapter also covers the limitations of a WSN along with various technologies available for deploying WSNs.

Section 2: Design and Deployment

Chapter 3: Design Model and Deployment Fashion of Wireless Sensor Networks

This chapter discusses the manner of WSN deployment. It also discusses the communication of sensors over a wireless link to unite the necessities of a specific application.

Chapter 4: An Algorithmic Approach to the Node Selection Problem in Industrial Wireless Sensor Networks

This chapter talks about the problem of placing a minimum number of sink nodes in a weighted topology such that each sink node should have a maximum number of sensor nodes within the given capacity, which is known as Capacitated Sink

Node Placement Problem. It also proposes a heuristic-based approach to solve this problem.

Chapter 5: Data Aggregation Scheme Using Multiple Mobile Agents in Wireless Sensor Network

This chapter presents an efficient data aggregation scheme based on an itinerary approach using multiple mobile agents aimed at accumulating and transferring data to the sink. It also presents a predefined set of experiments and compares the outcome for the proposed data aggregation scheme with existing ones.

Chapter 6: Data Collection Protocols in Wireless Sensor Networks

This chapter covers the classification of data collection protocols. The classification is done based on various parameters such as network lifetime, energy, fault tolerance, and latency. The chapter analyses different techniques to achieve these parameters.

Chapter 7: WSN for Event Detection Applications: Deployment, Routing, and Data Mapping Using AI

This chapter describes a query-processing framework for WSN that addresses many of the requirements associated with the vision of WSN as a database. By considering WSN as a database, a significant reduction in the cost of software engineering that implements a data collection program for the WSN can be achieved.

Chapter 8: Swarm Intelligence-Based Bio-Inspired Framework for Wireless Sensor Networks

This chapter examines swarm intelligence- and social insects-based approaches to deal with a bio-inspired networking framework. The chapter looks into various challenges and issues in the WSN field.

Chapter 9: Energy Saving Hierarchical Routing Protocol in WSN

This chapter examines and compares five protocols for extending the life of WSNs by minimizing energy consumption without affecting packet transmission. It begins with a discussion of the background of the WSN and the factors associated with energy utilization in sensor nodes.

Chapter 10: Research on Polling Control System in Wireless Sensor Networks

This chapter proposes a prioritized polling system that combines exhaustive service with gated service. The gated service is used in ordinary sites with low priority and exhaustive service is used at central sites with high priority. The average queue length and average waiting delay of the service model are accurately analysed by using embedded Markov chain and probability generating functions.

Chapter 11: Cross-Layer Inference in WSN: From Methods to Experimental Validation

This chapter addresses the fundamentals of distributed inference problems in WSNs and provides statistical theoretical foundations to several applications. It adopts a statistical signal processing perspective and focuses on the distributed version of the binary-hypothesis test for detecting an event as correctly as possible. The chapter also examines a reference WSN scenario-MIMO.

Chapter 12: Queries Processing in Wireless Sensor Network

This chapter proposes a similarity between the problem of selecting indexes and materialized views using the Knapsack algorithm. The contributions of the work are the use of the backpack algorithm to present this problem as well as mathematical modeling, followed by the use of machine learning to reduce the execution time of the workload.

Chapter 13: Interference Mapping in 3D for High-Density Indoor IoT Deployments

This chapter addresses deployment-signal interference of Internet of Things (IoT) devices occupying the same spectrum and signal fading due to the environment. It discusses the effects of fading and interference from other IoT devices working in the same frequency range.

Chapter 14: Applications of Prediction Approaches in Wireless sensor Networks

This chapter discusses WSN deployment environment, energy conservation techniques, mobility in WSN, prediction approaches and their applications in the sleep/wake-up periods of sensor nodes.

Section 3: Applications

Chapter 15: Innovative Wearable Sensors Based on Hybrid Materials for Real-Time Breath Monitoring

This chapter covers different aspects of the design and implementation of wearable biosensors woven into fabric. Weaving the sensors into fabrics gives flexibility to the user, allowing 24 hours of medical observation without causing discomfort. The focus of this chapter is on measuring the breathing pattern of individuals.

Chapter 16: An Evolutionary Perspective for Network Centric Therapy through Wearable and Wireless Systems for Reflex, Gait, and Movement Disorder Assessment with Machine Learning

This chapter discusses Network Centric Therapy for assessing reflex, gait, and movement disorders. Inherent aspects pertaining to Network Centric Therapy involve wearable and wireless inertial sensor systems, machine learning, and Cloud computing access for the acquired inertial sensor signal data.

Chapter 17: Challenges of WSNs in IOT

This chapter discusses the various challenges of integrating WSNs into the IoT, such as security, topologies, and so on. The limited resources of WSNs are the main concern when it comes to integrating them with the IoT. Integration makes it possible to access a sensor node from anywhere in the world. It implies that the sensor node is now open for any heterogeneous Internet user in the world.

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I would like to thank the chapter authors for their excellent contributions. I would also like to my wife, Suma, and son, Gangadhar, for their patience and understanding during the process.

Section 1

Overview

Chapter 1

Wireless Sensor Networks: Applications

Bhargavi Dalal and Sampada Kukarni

Abstract

Wireless sensor networks consist of small nodes with identifying component by sensing, computation, and wireless communications infrastructure capabilities. Many path searching means routing, power management, and data dissemination protocols have been specifically designed for WSNs where energy awareness is an essential design issue. Routing protocols in WSNs might differ depending on the application and network architecture. Wireless Sensor Networks (WSNs) provide several types of applications providing comfortable and smart-economic life. A multidisciplinary research area such as wireless sensor networks, where close collaboration in some users, application domain experts, hardware designers, and software developers is needed to implement efficient systems. The easy molding, fault tolerance, high sensing fidelity, low price, and rapid deployment features of sensor networks create various new and thrilling application areas for remote sensing. In the future, this wide range of application areas will make sensor networks an essential part of our lives. However, understanding of sensor networks needs to satisfy the constraints presented by factors such as fault tolerance, scalability, cost, hardware, dynamic topology, environment, and power consumption.

Keywords: Applications of Wireless Sensor Network

1. Introduction of wireless sensor network

Wireless sensor network (WSN) refers to a collection of sensors for observing, monitoring and recording the physical conditions of the environment [1]. After observing and recording the behavior of sensors, consolidating the collected data at a central location is the main task. WSNs measure environmental conditions like wind, humidity, temperature, pollution levels of sound, air and so on [2].

WSNs consist of spatially distributed and independent sensors to observe and monitor physical and environmental conditions. They are helpful to collectively pass recorded data through the network to a central location. Some of the networks are bi-directional, i.e. both collecting data from distributed sensors and supporting control of sensor activity.

Spatially dispersed and dedicated networks help to collect different parameters with special sensors which are included in the WSN. The development of WSN was motivated by mainly military applications such as battlefield surveillance. Nowadays, such networks are used in many applications like industry, consumer applications. Few of the applications such as industrial process monitoring and control, machine health monitoring, and so on.

2. WSN components

The main component of WSN is node. A sensor network generally consists of tens to hundreds or thousands of relatively small nodes, each equipped with one or more sensing devices [3]. Here each node is linked to one or numerous sensors. Each such node normally has several parts: a radio transceiver with an inner antenna or connection to an exterior antenna, a microcontroller, an electric circuit for interfacing with the sensors and an energy source, usually a battery or an implanted form of energy collecting. A node with a sensor implanted may vary in size. Size of a node can be from that of a brick to the size of a grain of dust. The cost of sensor nodes is also variable. They may range from a few to hundreds of dollars, depending on the complexity of the individual sensor nodes. The potential of different properties such as energy and its consumption, memory, computational speed and communications bandwidth varies the size and cost of sensor nodes. Hence, size and cost limitations on sensor nodes result in corresponding constraints on resources. The use of specific sensor nodes with required quality of various properties depends on the application.

The base stations are another important component of WSN. They are one or more components of the WSN with many more qualities like computation, energy conservation and communication to share recorded data. They play a role of gateway between sensor nodes and the end user. These gateways are usually useful to forward recorded data from the WSN on to a central location. Central locations are nothing but the servers. Other special components in WSN are routers. Routers specially designed to compute, calculate and distribute the routing tables.

As of now, we have seen very few but important components of WSN. Following **Figure 1** explains the various components of WSN.

1. Sensor Node
    a. Sensing Unit
        i. Sensor
        ii. ADC

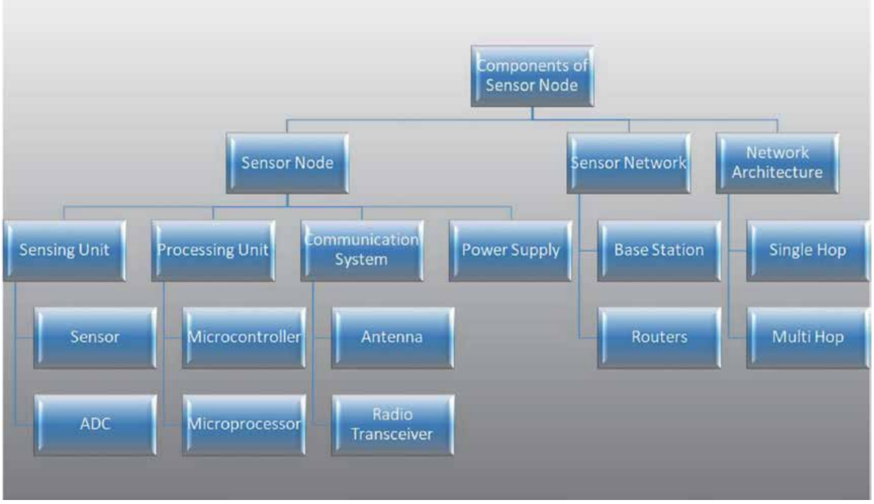

Figure 1.
Various components of sensor node.

   b. Processing Unit
      i. Microcontroller
      ii. Microprocessor
   c. Communication System
      i. Antenna
      ii. Radio Transceiver
   d. Power Supply
2. Sensor Network
   a. Base Station
   b. Routers
3. Network Architecture
   a. Single Hop
   b. Multi Hop

2.1 Sensor node

A sensor node is a combination of different subunits and all they help to perform the functionality of the sensor node. Different units help to sense, record, monitor and analyze the data which is collected from physical conditions [4].

Even though the name, a Sensor Node comprises not only the sensing component but also other important characteristics like processing of recorded data, communication with servers and storage units to store recorded data. With all these characteristics, components and enrichments, a Sensor Node takes responsibility for data collection, data correlation, and fusion of data from other sensors with its own data and network analysis.

Following figure depicts the same.

The above **Figure 2** shows the sensor node is a combination of different units. They are, sensing unit, processing unit, communication unit and power unit. All of them have their own responsibility to sense data, process data and communicate sensed and processed data to servers respectively. This can be done with the help of a power unit as all the components are low-power devices. And hence a small battery like CR-2032, is used to power the entire system.

The sensing unit comprises sensor and Analog to Digital Converter (ADC). Sensor collects the Analog data from the physical world and an ADC takes the responsibility of conversion of this Analog data to Digital form. The second unit is the processing unit, which is usually a microprocessor and/or a microcontroller. They perform intelligent data processing and manipulation. The next unit is a communication unit consisting of a radio system and an antenna. Here, radio transceivers are used for data transmission and reception and antenna helps to transmit and receive the signals.

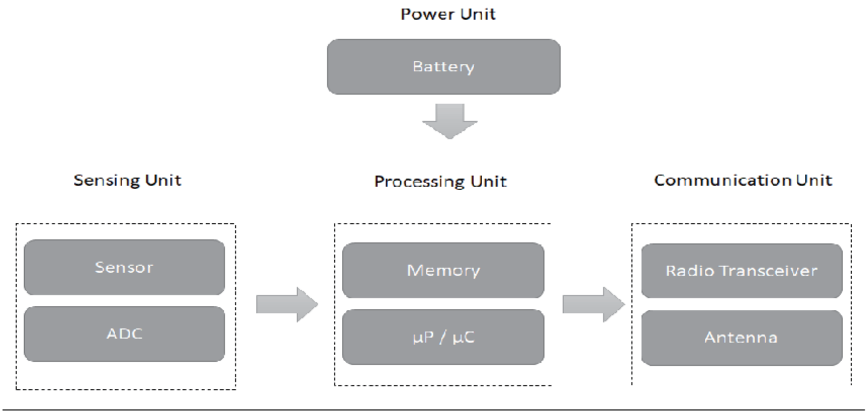

Figure 2.
Sensor node in WSN.

2.2 Sensor network

Till now we have seen that the sensor node collects information from the physical environment and transmits it to the sensor network. Now it's time to learn the sensor network. Sensor network consists of two components. They are namely base station and a router.

Base stations are often thought of as just a central component that is used to gather data from distributed nodes [5]. Here base station acts as a gateway between other networks through the internet. Once the base station receives the data from the sensor nodes, a base station performs some processing on collected data and sends the processed information to the user using the internet.

As we have seen previously, the main task of a sensor node is to sense data and send it to the base station. For the same, a routing path is essential. And this responsibility is handled by a second component of the sensor network. It is a router. For finding the efficient routing path from the source node to the base station there are a lot of proposed routing protocols. The design of routing protocols for WSNs must consider the power and resource limitations of the network nodes, the time-varying quality of the wireless channel, and the possibility for packet loss and delay.

2.3 Network architecture

To observe the behavior of sensors in sensor nodes, and then to communicate with the base station, they must connect through networking. Here is the role of the second component of WSN. It is network architecture. To observe a physical environment co-operatively, a huge number of sensor nodes are arranged in a massive area. That's why the networking of these sensor nodes is equally important. There is communication not only between sensor nodes in a WSN but also with a Base Station (BS) [6]. Here for this communication, WSN uses wireless communication. Hence, this network is named as wireless sensor network (**Figure 3**).

As mentioned above, here in network architecture, there is not only the communication between intermediate sensor nodes or between sensor nodes and base station, the base station also communicates with sensor nodes. The base station sends directions to the sensor nodes. The sensor node performs the task accordingly by working in co-operation with other sensor nodes in the network.

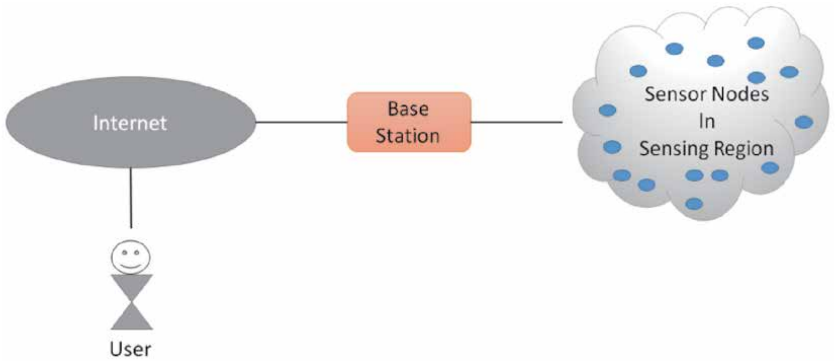

Figure 3.
Network architecture.

Here the network architecture has two main aspects. First one is a single-hop network architecture and the other one is multi-hop network architecture.

Figure 4 explains the concept of single-hop network architecture. In a Single-hop network architecture, each sensor node is connected to the base station. It allows long distance transmission as well. As it allows long distance transmission, obviously the energy consumption for communication will be significantly higher. And hence it affects the tasks of data collection and computation.

As we have seen the power consumption is significantly high in single-hop network architecture, this drawback is overcome in multi-hop network architecture. Hence, Multi-hop network architecture is usually used for better power consumption. **Figure 5** depicts the concept of multi-hop network architecture.

Due to intermediate nodes in multi-hop network architecture, the load of one single link between the sensor node and the base station reduces. Here the data is transmitted through one or more intermediate nodes. Hence, it is more efficient than that of single-hop network architecture.

Multi-hop network architecture can be implemented in twofold. Flat network architecture and Hierarchical network architecture. In flat architecture, the base station broadcast commands to all the sensor nodes but the sensor node with identical query will respond using its peer nodes via a multi-hop path.

In hierarchical architecture, a group of sensor nodes are formed as a cluster and the sensor nodes transmit data to consistent cluster heads. The cluster heads can then communicate the data to the base station.

Figure 4.
Single hop network architecture.

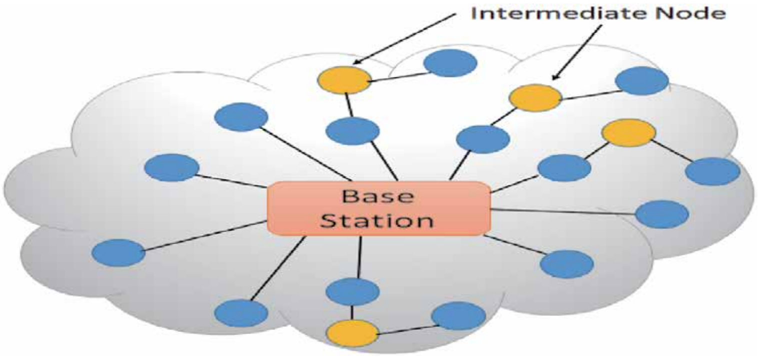

Figure 5.
Multi hop network architecture.

3. Characteristics of WSN

The important characteristics of a WSN include

- Power consumption limitations for sensor nodes.
- Ability to cope with failures of nodes.
- Mobility of nodes.
- Heterogeneity of nodes.
- Homogeneity of nodes.
- Ability to deploy on a large scale.
- Capability to survive harsh environmental conditions.
- Helps to use easily.

These are few major and common characteristics of WSN. But, the characteristics of wireless sensor networks for various applications may be quite different. They also can share common characteristics too.

Sensor nodes have been defined into two characteristics.

1. Static characteristics
2. Dynamic Characteristics

Although here as we mentioned above some characteristics, but now we are focusing on mainly these two characteristics.

3.1 Static characteristics

In fact, such as smart buildings, physical infrastructure or technical experimentations are some applications, where the network is stable i.e. static over the space, having several fixed components in the network is regular solution. The fixed parts would be connected to the continuous power supply, so that wireless parts can use low power to transfer data to them and also nodes can go in the standby mode from time to time (**Figure 6**).

The characteristics of some applications include low cost, small size, low power consumption, robustness, flexibility, resiliency on errors and faults, autonomous mode of operation, and often privacy and security.

3.2 Dynamic characteristics

An active care approach that is dynamic works as an 'on-the-fly'-based initiating technique that creates a fresh topology when the existing one is no longer ideal. The main advantage of its capability is to create an active prior version, that the system becomes more energy-efficient. These networks are characterized by a need for low power consumption and low levels of physical security and broadcast physical medium. Asymmetric techniques like RSA are not to be used as are inefficient and consume too much power.

3.2.1 Ad-hoc network like MANET

MANET means Mobile ad-hoc Network. It is also named as wireless ad hoc network or temporary wireless network. It usually has a searching path interacting environment on top of a Link Layer ad-hoc network. They consist of set of mobile nodes connected wirelessly in a self-configured, self-healing network without having a fixed infrastructure [7]. These wireless sensor nodes are allowed to move freely on a random basis as the network topology changes frequently. Each node acts as a router as they accelerate traffic to other specified nodes in the network.

Figure 7 shows the structure of an ad-hoc network which consists of a peer-to-peer, self-forming, self-healing network. Typically communicate at radio frequencies (30 MHz-5GHz).

Reconfiguration can be made in such a way that the new network has the same topology (only some nodes have exchanged their places) or allowing any arbitrary topology, also, it is not necessary to modify the routing algorithm.

Figure 8 shows clustered-based wireless sensor networks have been extensively used in the literature in order to achieve considerable energy consumption

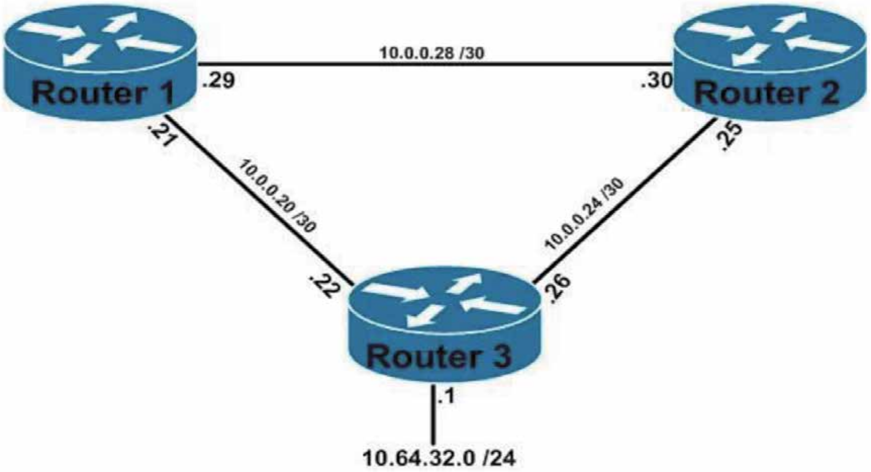

Figure 6.
Structure of static network.

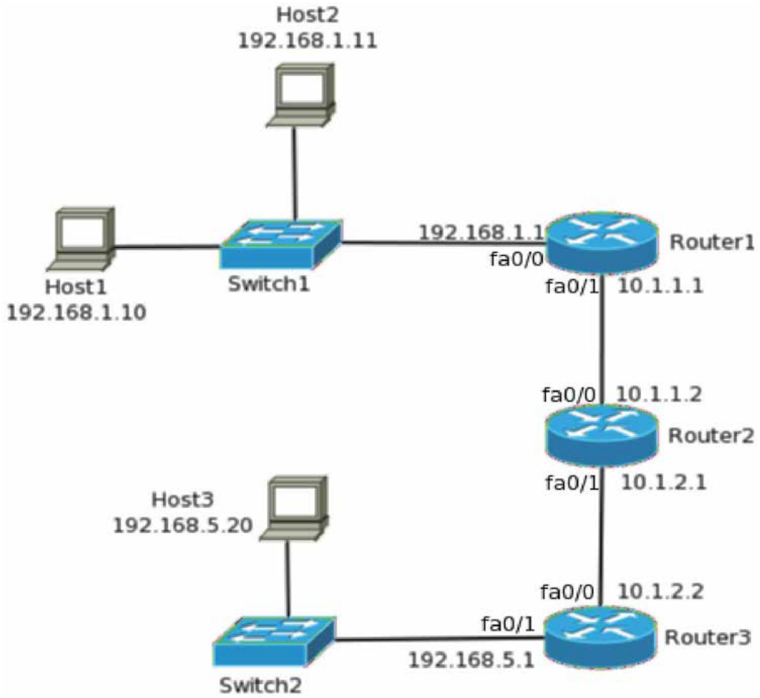

Figure 7.
Structure of ad-hoc networks.

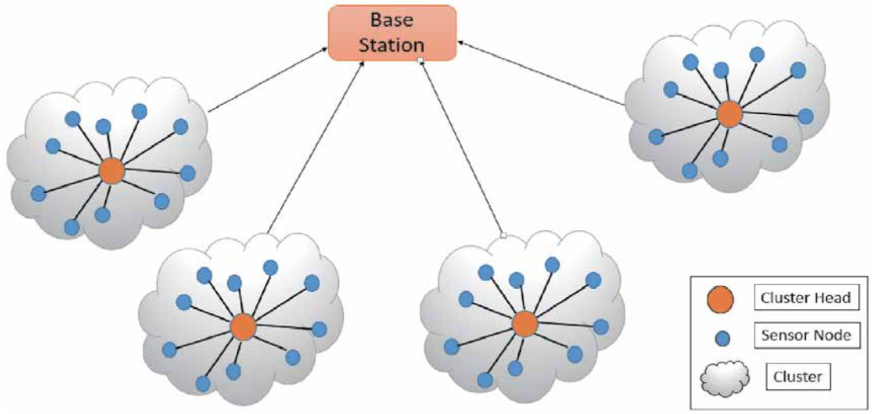

Figure 8.
Clustered-based wireless sensor network.

reductions. The cluster formation phase, where all the dynamic nodes transfer a control packet focused to the sink node in order to be a portion of the cluster. Precisely, the lively active nodes in the managed that controlled area where control packet transmit with possibility 'τ' in each time slot. If there is only a single communication that is only one node transfer, the control packet is well received by the sink node, and the node that successfully transmitted this packet is considered to be already an adherent of a cluster.

As such, this node no longer transmits in the cluster formation phase. The remaining nodes continue this process until all the active nodes successfully transmit their control packet. If there are two or more transmissions in the same time slot, all transmissions are considered to be corrupted, and the control packets involved in this collision have to be retransmitted in future time slots. Hence, when a collision occurs, none of the involved nodes are aggregated to a cluster.

3.2.2 Some common characteristics

Many of the characteristics may depend on the applications. In some of the applications, it might be acceptable or in some of the applications it might not be that much considered. So, few are the characteristics are common.

Following are the common characteristics that need to be considered while using WSN for developing different applications.

1. Power Efficiency
2. Low power
3. Responsiveness, energy constraint
4. Reliability
5. Data compression
6. Scalability
7. Mobility

Let us see all above mentioned characteristics one by one in detail.

4. Power efficiency

The consumption of Power limits for nodes with batteries. Many of the challenges of sensor networks revolve around the limited power resources. The size of the nodes limits the size of the battery. The software and hardware design needs to carefully consider the issues of efficient energy use. Specific power-management strategies are necessary for WSN nodes that are powered by non-rechargeable batteries.

It is mandatory to note the power eating features of the node in three components. They are the sensing circuitry, the digital processing unit, and the radio transceiver unit.

The sensing circuitry, which consists of the environmental green sensors and the ADC, needs energy for bias currents, as well as amplification and analog filtering.

A node's digital processing circuits are typically used for digital signal processing of gathered data and implementation of the protocol stack.

Two-way communication through radio transceiver unit with other nodes and a remote base station is achieved through a network processor, which packetizes and encodes the data for robustness and security.

5. Low power

The key to accomplish a longer lifespan for WSN is to design with minimal power consumption of wireless sensor nodes, hence titled “low power”. To reduce the overall power consumption, low power WSN controls the lively active time or "awake time" of the devices (such as a radio or microcontroller) and limits the present draw when they are "sleeping." These networks accomplish this by changing the power setting modes of the devices, such as "always on", "standby", or "hibernation" modes. Depending upon the requirement, the nodes and its components may be used in different power setting modes. As the energy policy depends on the application; in some applications, it might be acceptable to turn off a subset of nodes in order to conserve energy while other applications require all nodes operating simultaneously. It helps to work WSN in low power mode.

6. Responsiveness

The sensor nodes need to become independent to work even in bad situations and portrait responsiveness. WSN works more efficiently if sensor nodes develop characteristics of responsiveness without explicit user and/or administrator action. If the network is more responsive, it yields more throughput and obviously increases the efficiency of the network.

7. Reliability

WSNs involve a number of sensor nodes with limited processing, storage, and battery capabilities. The overall reliability of a WSN is enhanced by the reliability of the components of the node. If either of the components fails, the whole node fails. Each component/unit has associated reliability and defined in the software/hardware specification. There are numerous approaches to cut down the power consumption of WSN nodes (increases the network lifetime) and increase the reliability of the network (by improving the WSN quality of facility). As the reliability increases, obviously the capability of the network increases.

8. Data compression

While designing the WSN, it is necessary to reduce the amount of energy used for radio transmission, but nodes can use additional energy for computation and/or filtering. This can be fruitful if data is compressed.

9. Scalability

Scalability of routing protocols used in WSNs is an acute topic due to the tremendously high number of nodes and comparatively high node compactness. A good routing protocol has to be scalable and easily adaptive to the changes in the network topology. Performance of protocol must well as the network grows larger or as the workload increases.

10. Mobility

Mobility in wireless sensor networks is an element which directly influences the network performance. Indeed, with an architecture based on the IP stack, a mobile

Sr. No.	Characteristics	Importance of Characteristics
1	Power Efficiency	This characteristic insists to minimize the power eating property of the node. More power efficient network yields more effectiveness.
2	Low power	The key to achieving a longer lifetime for WSN is to design WSN that minimizes power consumption of wireless sensor devices.
3	Responsiveness	Sensor networks need to become autonomous and exhibit responsiveness without explicit user or administrator action.
4	Reliability	Reliability of the network increases the throughput of the WSN.
5	Data Compression	Nodes can use additional energy for computation and/or filtering. Data compression helps to reduce the stress of the node in WSN.
6	Scalability	A good and adaptive (adapts the changes in the network topology) routing protocol makes the WSN more scalable.
7	Mobility	This characteristic helps to maintain connectivity of mobile nodes with other sensors, also allowing connectivity to the Internet.

Table 1.
A briefed view of characteristics.

node has to maintain connectivity with other sensors, also allowing connectivity to the Internet.

All above mentioned characteristics have their own importance. **Table 1** is a briefing about all the characteristics one by one.

Let us see all above mentioned characteristics in detail along with some applications. Here, applications are included to explain how different characteristics are helpful while developing diverse applications. Keep in mind that these characteristics have their own importance while developing the applications. It's not at all necessary that every characteristic plays a vital role in every application. But, commonly all they help to increase the productivity, efficiency and throughput while developing the application.

Mainly, we are considering three applications while studying the above mentioned characteristics. They are viz. a. Health Monitoring System, b. Military Application and c. Security and surveillance.

a. **Health Monitoring System:**

Here, we will see how above mentioned characteristics are important while developing the Health Monitoring System using WSN. The Bio-compatible wearable sensors allow vast amounts of data to be collected and mined for clinical trials, reducing the cost and inconvenience of regular visits to the physician. There are many aspects in which the health monitoring system works. Like, some advanced techniques are used to track diabetes using a WSN or A blood pressure sensor suitable for wireless biomedical applications. Patients can be tracked and monitored in normal or in emergency conditions at their homes, hospital rooms and also in Intensive Care Units (ICUs) [8]. To develop any of the applications in the Health Monitoring System, let us see how the above mentioned characteristics play a role.

b. **Military Application:**

When WSN is used while developing military applications, again there is a need to think about the importance of above said characteristics. Video sensing is useful in various applications such as: military, environmental, healthcare, industries and surveillance of all its types [9]. To make an application efficient, it's not at all necessary to incorporate all characteristics. But, those who help to improve the throughput should get consideration while developing the application. As said above, this military application also has many aspects. WSNs can be used by the military for a number of purposes such as Monitoring or Tracking the Enemies, for Force Protection or for Vehicle Navigation systems for the military and so on.

c. **Security and surveillance:**

Each sensor node should have sufficient security mechanisms in order to prevent unauthorized access, attacks, and unintentional damage of the information inside of the sensor node [10]. For this type of application, the nodes are placed at fixed locations to continuously supervise some parameters in order to detect possible anomalies like a fire, a toxic gas, or even a roof failure using micro seismic and rock deformation sensors. Here again, while developing the required application, if important characteristics are taken in consideration, then the developed application will give more efficient results.

Ultimately we have seen that the consideration of characteristics while developing any of the applications helps to give high, accurate and efficient results. **Table 2** helps you to understand the importance of characteristics in all respective applications.

Sr. No.	Characteristics	Importance of Characteristics	Health Monitoring System	Military Application	Security and surveillance
1	Power Efficiency	This characteristic insists to minimize the power eating property of the node. More power efficient network yields more effectiveness.	With more battery life, any Health Monitoring Application works for a longer time. Longer life sensors can monitor the sugar level in case of Diabetes Monitoring system and blood pressure level in case of BP Monitoring system very effectively. If the foreign body needs to embed in the human body, then this characteristic is most important.	As the nodes are dispersed in the field, it's not easy to change or charge the batteries. Power efficient nodes used in many applications in Military is useful for monitoring and protecting military forces from intruders.	In these types of applications, nodes are placed at the same location. They can be charged or changed as and when required. Hence, if this characteristic is avoided upto some extent, then there will not be any harm in the system.
2	Low power	The key to achieving a longer lifetime for WSN is to design WSN that minimizes power consumption of	To increase the battery life, power modes are very helpful. From different components of sensor nodes, we	In many of the military applications, they are developed to monitor the movement of intruders. To	In this application, again, all nodes have to work without sleeping.

Sr. No.	Characteristics	Importance of Characteristics	Health Monitoring System	Military Application	Security and surveillance
		wireless sensor devices.	cannot put the sensor in sleep mode as the sensor has to collect reading continuously in either Diabetes Monitoring System or BP Monitoring System. But the transceiver unit can be on sleep mode when there is no transmission or receiving of data.	achieve this goal, all required nodes and their components have to work continuously. This characteristic cannot be fulfilled in case of many military applications as we cannot put nodes in sleep or in hibernate mode.	
3	Responsiveness	Sensor networks need to become autonomous and exhibit responsiveness without explicit user or administrator action.	To develop a Health Monitoring System, sensor nodes must be responsive to collect data regularly without fail. Nodes have to work autonomously.	In Military Application, sensor nodes must be responsive to collect data frequently without fail. To be responsive, to monitor the actions of the enemy, the network has to work independently in case of any failure.	Here also sensor nodes must be responsive to collect data repeatedly without fail. If the network is not responding continuously, then it will become difficult to give required security in current application.
4	Reliability	Reliability of the network increases the throughput of the WSN.	In account of correctness of reading in case of either application of the Health Monitoring System, reliability characteristics must be reflected while implementing. To detect the sugar level or to monitor BP, the nodes must be reliable. Nodes must read all the readings correctly and reliably. Every component and unit must be capable of handling the unfortunate situations.	To increase the efficacy, all military applications must be implemented with consideration of reliability of sensor networks. Reliability can be increased here by developing nodes who support low power consumption.	With the characteristic reliability, the application of security and surveillance provides more security which is the objective for development of this application. Reliable network supports the security application in case of failure of any of the components or nodes, the whole network must give the required throughput.

Sr. No.	Characteristics	Importance of Characteristics	Health Monitoring System	Military Application	Security and surveillance
5	Data Compression	Nodes can use additional energy for computation and/or filtering. Data compression helps to reduce the stress of the node in WSN.	Data compression and transmission increasingly important in the field of computer communication. Computer-based modeling applications should important to-evaluate medical data communications.	Information processing, fusion, and knowledge generation can significantly enhance the capabilities of military applications of WSNs. It needs to have reliable correlation between all nodes and after data compression challenge is to get processes information efficiently towards destination.	Sequence of characters, image based data, encode multiple correlated data streams when data get compressed for easy reception at destination and need security.
6	Scalability	A good and adaptive (adapts the changes in the network topology) routing protocol makes the WSN more scalable.	Network must respond efficiently in case of changes to the network. If it is a Health Monitoring system, the network must be scalable and adaptable while collecting accurate information.	Routing protocols must perform well as the network grows larger or as the workload increases. Mainly in Military application, the network must be scalable and dynamic in case of any changes so that it can serve effectively.	If the load increases, the network must be scalable. Otherwise, security application cannot give required results.
7	Mobility	This characteristic helps to maintain connectivity of mobile nodes. The performance of the protocol is analyzed for mobility in large networks as well.	In all applications, mobility also plays an important role. In the case of a speed. How health monitoring system can be worked is a big challenge.	In the case of a Military Application, the energy of nodes when moving in sensor environment. And work efficiency also challenging point.	Challenging point is that when nodes coming in working environment where they have to communicate with each other. If any malicious node come through freely moving environment that communication should be very dangerous for all other nodes.

Table 2.
Importance of characteristics with applications.

11. Challenges in wireless sensor nodes in various ways for an application

Challenges in WSN are listed in **Table 3**.

Sr. No.	Parameter	Description	Challenges
1	Energy	Energy is an important factor for sensor lifetime. Energy is consumed for node operations sensing, data collection and network operations like data communications via different communication protocols.	To manage limited battery by designing and implementing various energy efficient hardware and software protocols for WSN.
2	Self-Management	Wireless sensor networks once deployed should be able to work without any human intervention. It should be able to manage the network configuration, adaptation, maintenance, and repair by itself	To manage various unpredictable changes which occurred in the environment like in remote areas and harsh environments, without infrastructure support or the possibility for maintenance and repair they need self-configuration.
3	Hardware and Software Issues:	Energy is an important factor for sensor lifetime. Energy is consumed for node operations sensing, data collection and network operations like data communications via different communication protocols. Platforms which can adapt to run-time situations will play an important role in wireless sensor networks. Hardware/Software configuration move forward complex operations and provides a flexible or easy way for communication mechanisms to deal with complex network structures. Due to small size the nodes have also restricted resources such as CPU performance, memory, communication bandwidth and range. The range of sensor nodes can cover a limited area of the physical environment.	The traditional sensor node architecture, which has software implementation running on a fixed hardware design, is no longer fit to the changing requirements for new upcoming technology. The operation behavior changes because of the application requirements and the environmental conditions To collaborate with other already deployed sensor networks and to maintain an efficient network structure, the sensor nodes require flexible communication capabilities.
4	Operating System	Operating Systems for WSNs should be less difficult than the general operating systems. Application developers create interfaces between the user and the computer hardware and controls the execution of all kinds of programs.	It should have a stress-free programming paradigm. They should be able to concentrate on their application logic instead of being concerned with the low level hardware issues like scheduling, preempting and networking.
5	Quality of Service (QoS)	Quality of service is the needed service which is provided by the sensor networks to its users. Though, it is hard to say, due to the dynamic nature of network topology, and the available state information for routing is inherently rough.	Sensor networks need to be complete with the required volume of bandwidth so that it is able to achieve a minimal required QoS. QoS is a tool that should be designed for an unstable QoS constrained traffic. Many times scalability is the important part of a sensor network. Adding or removing of the nodes should not affect the QoS of the WSN.

Sr. No.	Parameter	Description	Challenges
6	Security	In sensor networks, when there is a consideration of security it is vital for each sensor node and the base station to have the capacity to verify that the data received was really sent by an authentic sender and not by an opponent that tricked legitimate nodes into accepting incorrect data.	Confidentiality is required in sensor networks to protect information traveling from one sensor node to another sensor node of the network. Privacy required in between sensors and base station.
7	MAC Layer Issues	Direct impact on energy consumption, primary causes of energy waste are found at the MAC layer such as collisions, control packet overhead and idle listening.	Power redeem forward error control difficult technique to implement due to its heavy computing power requirements and the fact that long packets are normally not practical.
8	Architecture	Architecture can be considered as some protocol for implementing some functionality along with a set of interfaces, functional internal components, protocols and physical hardware devices.	Limited features in sensor network architecture make difficulties in this field in terms of progress. Durability and scalability is a prime factor in architecture.
9	Data Collection and Transmission	Data collection and decisions is the main objective of sensor nodes. The sensors frequently sense the data from the surrounding environment, process it and transmit it to the base station infrastructure or sink.	Sometimes the specimen of data collected is redundant and it's not necessary to transmit such samples to the sink node as it will only consume energy. So care is important during data collection and transmission.
10	Calibration	Calibration is like a one standard process of adjusting the raw sensor readings collected from the sensors into corrected values by comparing it with some standard values.	Manual calibration or basic reading which is taken for sensors is time consuming and a difficult task. Due to failure of sensor nodes and random noise which makes manual calibration of sensors too expensive.
11	Deployment	Deployment in which implementation of the wireless sensor network takes place in real world location. At some places which are hard to reach, sensors are dumped from helicopters or may be in some locations sensors are placed according to some network topology.	Energy management issues like discharged battery recharge and replacement are cumbersome challenges in real world scenarios. Due to many concurrent transmission attempts made by several sensor node networks, network congestion yields low data.
12	Limited Memory and Storage Space	A sensor is a small device with only a small amount of memory and storage space for the code.	For an effective security mechanism, it is needed to limit the code size of the security algorithm. Building software for the sensor must also be quite small due to limited code size and memory.

Table 3.
Challenges in WSN.

12. The major applications of WSNs

12.1 Application of WSNs

1. **Logistics**

Logistics is a multi-player business which has changed significantly in the last decade. e.g. transport of food. **Figure 9** shows one application scenario, where

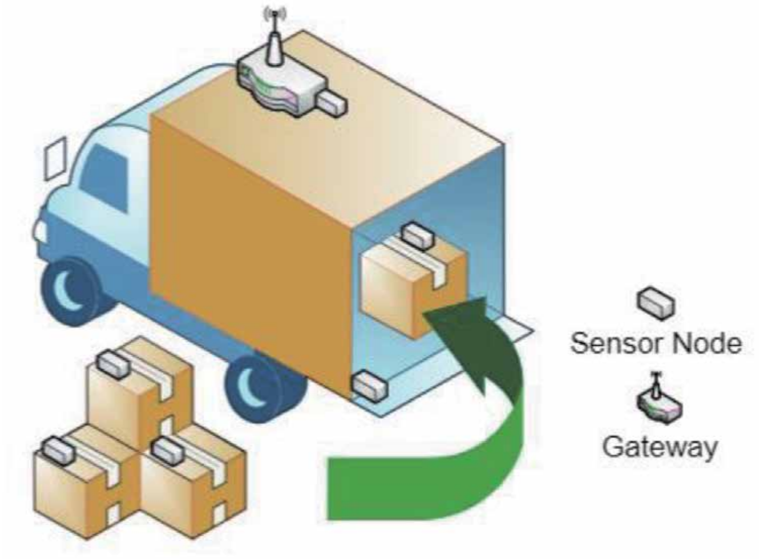

Figure 9.
Wireless sensor network for logistics.

wireless sensor network nodes are connected to goods (mostly food because of their perishable nature). The goods are loaded from a storehouse or warehouse to a good carrier vehicle, in which their nodes need to be self-organize and form a network of nodes, which can forward information of the goods' from one state to the outside world using a gateway (e.g. a telematics unit).

Logistics benefits clearly from Wireless Sensor Networks. However, the requirements of logistics for applicable WSNs are challenging.

2. **Environmental monitoring**

Simple computations and to send/receive data performance done by the sensor nodes. These nodes are small in size and are embedded into devices. Data collection is the typical usage where data collected from the surrounding environment via sensors. Environment monitoring has become an important field of control and protection, providing real-time systems and control communication with the physical world. During data collection sensor nodes

- Monitor and manage air quality,
- Monitor and manage conditions of traffic,
- Monitor and manage weather situations.

Characteristics of an environmental monitoring system

- Autonomy. Batteries must be able to power the weather stations during the whole deployment.
- Reliability. The network has to perform simple and predictable operations, to prevent unexpected crashes.

- Robustness. The network must account for a lot of problems such as poor radio connectivity (e.g., in case of snow fall) or hardware failures.
- Flexibility. One must be able to quickly add, move, or remove stations at any time depending on the needs of the applications.

3. **Industrial supervision**

   The advances in wireless communication, microelectronics, digital electronics, and highly integrated electronics and the increasing need for more efficient controlled electric systems make the development of monitoring and supervisory control tools the object of study of many researchers.

4. **Intelligent buildings**

   Wireless Sensor Networks (WSN) has become cardinal towards the implementation of smart homes, and they are proved to be a permitting technology for assisted living. WSNs are deemed appropriate for placement in home environments for diverse applications.

5. **Military applications**

   WSNs consist of a large number of small sensor nodes. Costing of small nodes is also less expensive. In military operations, there is always a threat or security challenges of being attacked by enemies. So if regular use of small nodes which is less expensive help to reduce the loss.

Figure 10 shows wireless sensor networks for military application. This application provides suitable sensors which can be used in top secret missions. These sensors can detect, identify and classify threads based on the count, number, whether it is armored vehicles or men in foot, type and amount of weapons they carry, etc., can be detected in advance. This application provides reliable real time war pictures and better situational awareness.

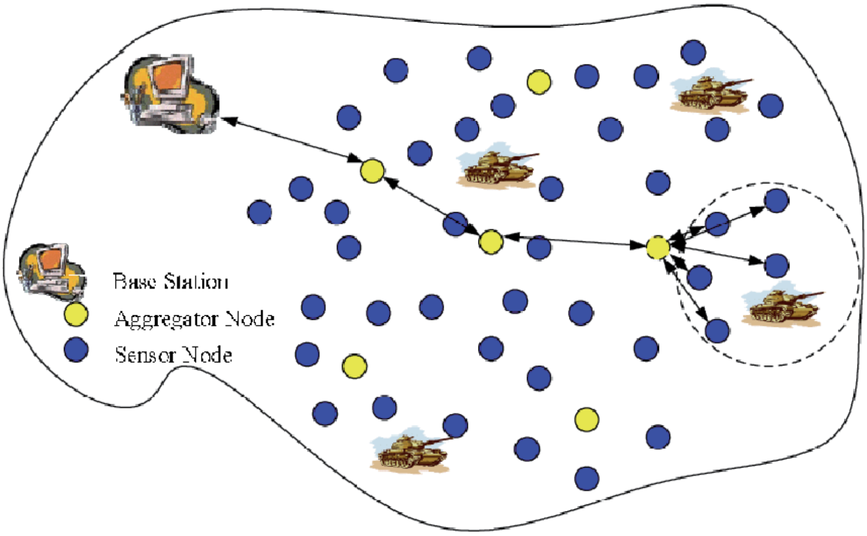

Figure 10.
Wireless sensor network for military application.

13. Conclusion

- Each such sensor network node typically has many parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source, usually a battery or an embedded form of energy harvesting.
- A sensor node might vary in size and size can be a size of a grain of dust.
- Sensor collects the analog data from the physical world and an ADC converts this data to digital data.
- When a large number of sensor nodes are deployed in a large area to cooperatively monitor a physical environment, the networking of these sensor node is equally important
- In flat architecture, the base station sends commands to all the sensor nodes.
- In hierarchical architecture, a group of sensor nodes are formed as a cluster and the sensor nodes transmit data to corresponding cluster heads.
- Wireless sensor network mainly consists of sensor nodes. A wireless sensor network consists of many different components.
- The static parts would be connected to the constant power supply, so that wireless parts can use low power to communicate to them and also nodes can go in the standby mode from time to time.
- A dynamic maintenance approach works as an 'on-the-fly'-based triggering technique that creates a new topology when the current one is no longer optimal.
- MANET stands for Mobile ad-hoc Network also called as wireless ad hoc network or ad hoc wireless network that usually has a routable networking environment on top of a Link Layer ad hoc network.
- The key to achieving a longer lifetime for WSN is to design wireless sensor networks that minimize power consumption of wireless sensor devices, hence the name "low power".
- Challenges in wireless sensor node in various ways for an application.
- The major applications of WSNs
- The goods are loaded from a warehouse to a freight vehicle.
- Their typical usage is to gather information about their environment via sensors, to potentially pre-process these data, and to finally transmit them.
- Characteristics of an environmental monitoring system

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Chapter 2

Wireless Sensor Networks: Applications and Challenges

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Abstract

Wireless sensor networks (WSNs) allow innovative applications and involve non-conventional models for the design of procedures owing to some limitations. Due to the necessity for low device complication and low consumption of energy, an appropriate equilibrium among communication and signal processing abilities should be instituted. This stimulates an enormous effort in research actions, standardisation procedure, as well as manufacturing investments on this aspect since the preceding years. Therefore, this chapter aims at presenting a summary of WSNs machineries, foremost applications and values, structures in WSNs project, and the developments drawn from some evidence and meta-data-based survey and assessments. Precisely, some applications, such as those based on ecological monitoring, and design approaches that emphasise a real implementation are discussed briefly. The trends and conceivable developments are outlined. Emphasis is given to "the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 technology" that enables several applications of WSNs. Hence, it is anticipated that this chapter would serve as an introductory aspect on the applications and challenges of WSNs for persons interested in WSNs.

Keywords: applications, device, IEEE, models, technology

1. Introduction

Presently, wireless sensor networks (WSNs) have created a growing attention from researchers and other stakeholders both in the industries and governments sectors [1–11]. Generally, WSN could be defined as a small system of nodes which accommodatingly sense, monitor, capture, process and control situations such as data/signals around an application, supporting dealings between peoples/computer systems and the immediate surrounding [12–14]. Hence, these nodes are resource-deprived and simultaneously very dependent on battery control, storing capacities, multiplication, size of data/signals and available bandwidth [7, 14]. Ordinarily, these nodes are static in a specific way and are left as a sole node in an isolated and human-remote point to implement tracing and recording of data.

The term wireless has turned into a generic and extensively comprehensive term employed to describe communications in which electromagnetic waves (EMWs) are employed in sending signal to several or the entire path of the communication [15].

According to Tiwari et al. [16], wireless networks (WNs) are any category of computer system that applies wireless statistics networks to plug system nodes. They are computer systems which are usually not connected by cables irrespective of the category. The application of a wireless system aids enterprises to avoid the expensive means of making use of cables for buildings or connecting different equipment settings. The basis of any wireless systems is the radio waves/microwaves, and their application that ensues at the physical advanced level of network construction both for radio waves/microwaves, radio communications systems (RCSs) and other relevant EMWs [17–20]. These radio waves/microwaves, RCSs and other relevant EMWs as well as mereological variables are useful in the propagation of the refractivity indices in the atmosphere [21–25].

Even if WSNs have been reported to have all it takes to allow innovative applications and by so doing contribute greatly to the innovative potential markets, there is also some possibility that the design of some WSNs is affected by several limitations which call for innovative models. According to Verdone [13], the action of detecting, processing and communication under restricted quantity of energy, explodes a cross-layer design method that characteristically necessitate the combined contemplation of circulated data/signal processing, intermediate access control and communication procedures.

Wireless machineries vary in several dimensions, most remarkably in what extent is the bandwidth they offer and the extent of the distance between the communicating nodes. Other vital differences which are included are possibly the electromagnetic fields (EMFs) they indicate and precisely the extent of the power them consume; this is greatly significant to mobile nodes [16]. As reported by Tiwari et al. [16], the four prominent wireless technologies are; "third-generation or 3G cellular wireless, Bluetooth (802.15.1), WiMAX (802.16) and Wi-Fi (more formally and generally known as 802.11)."

Presently, one of the utmost conventionally employed WSNs links is typically asymmetric; implying that both endpoints are typically categories of nodes [16]. Occasionally, one endpoint is called the base-station (BS), usually without mobility, but with a wired (or at top high bandwidth) connected to other networks such as internet. The node at the reverse end from the connection since a "client node" could habitually be transportable and employs its link to the BS for its communication with other nodes [11].

WSNs have grown substantially over the years and have a momentous potential in diverse applications in areas of environmental science, medical sciences, telecommunications, education services, agriculture, surveillance, military services, etc. [3, 26–29]. It has been reported that notwithstanding the influential capabilities of WSNs, their effective development is still somehow stimulating and challenging [1–3, 26, 28, 30, 31]. Presently, in deploying WSNs, some programming procedures have been anticipated, which emphasis mostly on issues of low-level-based (LLB) systems. However, for the simplification of the design of WSNs and abstract from technological LLB specifics, high-level-based (HLB) methods have been developed and some advantageous resolutions have been anticipated [3].

Hence, in this chapter an attempt will be make at presenting an overview of WSNs machineries, some of the primary applications and values, structures in WSNs project, developments and challenges drawn from some evidence and meta-data-based survey and assessments, which is anticipated to serve as an introduction on the applications and challenges of WSNs for persons interested in WSNs.

2. Categories of wireless networks

According to Tiwari et al. [16], there are essentially five categories of WNs as illustrated in **Figure 1**.

A brief description of these essentially five categories of WNs are highlighted below.

2.1 Wireless personal area network (wireless PAN)

This is a WSN that is carried over a low-powered, short-distance WN technology such as Bluetooth network, IrDA, wireless USB or ZigBee. The reach of a wireless PAN differs from a few metres to a few kilometres.

2.2 Wireless local area network (wireless LAN)

This is a WSN or wireless computer network (WCN) that links or connects two or more devices by means of wireless communication (WC) to form a LAN within a restricted location such as a computer research laboratory, household, institution, or workplace. This gives users the capability to move from place to place within the said location and remain connected or linked to the WN. Wireless LAN could also offer a connection to the wider cyberspace (internet) through a gateway. Most contemporary wireless LANs are based on the standards of IEEE 802.11 and are marketed under the Wi-Fi product designation. Wireless LANs have become prevalent for use in the several households, as a result of their ease of installation and use. They are also prevalent in commercial physiognomies that offer wireless access to their workforces and clients.

2.3 Wireless metropolitan area network (wireless MAN)

This is a computer network (CN) that communicates and interconnects users with various computer resources in a geographic location of the size of an urban area. The term MAN is applied to the interconnection of LANs in an urban area into a single greater network which could similarly offer effective connection to a wide area network (WAN). Wireless MAN is also used in describing the interconnection of several LANs in an urban region via the use of “point-to-point connections” between them [32].

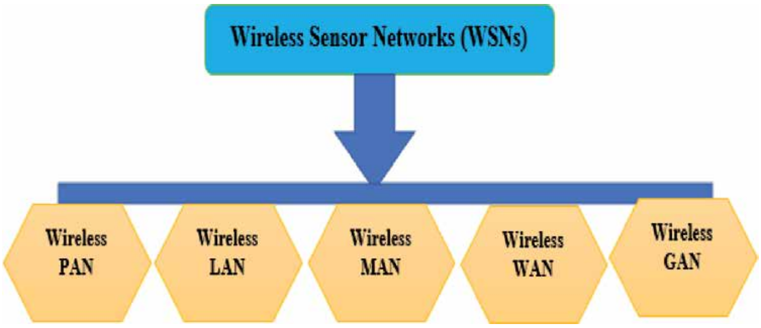

Figure 1.
Categories of WNs.

2.4 Wireless wide area network (wireless WAN)

This is another form of WN. The greater size of a WAN compared to a LAN entails the modifications in technology. WNs of diverse dimensions deliver data in the form of web pages, telephone calls and streaming video. A wireless WAN often differs from wireless LAN by using mobile telecommunication cellular network (MTCN) machineries such as 2G, 3G, 4G LTE, and 5G in transferring data. Wireless WAN is sometime called mobile broadband (MBB). These machineries are existing nationally, regionally, or even globally and are provided by a wireless service provider (WSP). Wireless WAN connectivity permits a user with a CN and a wireless WAN card to surf the network, check electronic mail, or connect to a virtual private network (VPN) from somewhere within the boundaries of WNs. Several CNs could assist in the integration of wireless WAN proficiencies. A wireless WAN could also be a closed network that covers a huge geographic location. For instance, a "mesh network or MANET" with nodes on towers, trucks, planes and buildings. It could also be a "low-power, low-bit-rate (LBR) wireless WAN, (LPWAN)," proposed to carry minor packets of information between things, habitually in the form of battery-operated sensors. Since the RMSs hardly offer a physically protected connection path, the wireless WANs characteristically integrate "encryption and authentication" approaches to make them more protected. Reportedly, several early GSM encryption procedures are imperfect, and security professionals have issued cautions that MTCN, including wireless WAN, is not that secure [32].

2.5 Wireless global area network (wireless GAN)

This refers to any network that is composed of diverse interconnected CNs (WANs) and also covers an unrestricted geographical location. It is apprehensively identical with Internet, which is considered as a GAN. Unlike LANs and WANs, GANs cover a much larger geographical area. Since GANs are used for supporting MTCNs across a number of wireless LANs, one of the main challenges for any wireless GAN is in transferring of the user communications from one LAN to another. One of the utmost popular wireless GAN categories is a broadband (BB) wireless GAN. The BB wireless GAN is a worldwide satellite Internet network (SIN) that employs transferrable terminals for telephony. The terminals connect CNs located in LAN to BB Internet.

3. The IEEE 802.15.4 technology

The "IEEE 802.15.4 wireless technology" is a "short-range communication system" which is planned to offer applications with comfortable throughput and potential necessities in Wireless PAN [4]. The main features of the "IEEE 802.15.4 wireless technology" as reported by Buratti et al. [4] are; inexpensive, truncated complexity, low consumption of power, truncated transmission data rate, to be maintained by inexpensive either fixed or moving means. One of the foremost fields of applications of this technology is the implementation and execution of WSNs.

The "IEEE 802.15.4 Working Group (the IEEE 802.15.4 Working Group) as noted by Buratti et al. [4], emphases on the standardization of the lowest two layers of the "ISO/OSI protocol stack" [33]. There are two possibilities for the higher layers characterisation, viz.; Zigbee protocols, specified by "the industrial consortia ZigBee Alliance (the industrial consortia ZigBee Alliance) and 6LowPAN. Some technical specifics interrelated to the "physical and MAC layers" as well-defined in the standard are would be briefly discussed [34]. Also, some physiognomies interrelated to advanced layers would be presented, bearing in mind the "Zigbee and 6LowPan," with specific consideration to the former [35].

3.1 The physical layer of the IEEE 802.15.4

Buratti et al. [4] in their study reported that "the IEEE 802.15.4" main system comprises of a "radio frequency (RF) transceiver and the procedure stack," as illustrated in **Figure 2**.

According to Buratti et al. [4], the "802.15.4 physical layer" functions basically in three diverse unrestricted/unlicensed bands (as well as with the diverse modalities) in respect to the geographical location where the system is positioned or installed. Nevertheless, spread spectrum procedures are somewhere required for the reduction of the interference extent/range in shared unrestricted/unlicensed. The "IEEE 802.15.4" requires a total of "27 half-duplex channels" transversely on the three frequency bands. The organisation is as follows:

- **The 868 MHz band:** This is just a channel with data rate availability of 20 kbps, with −92 dBm RF sensitivity essential and superlative (ideal) transmission extent is roughly 1000 m

- **The 915 MHz band:** This has ten channels with rate availability of 40 kbps; the receiver sensitivity and the superlative transmission extent are also roughly 1000 m;

- **The 2.4 GHz ISM band:** This has sixteen channels with data rate availability of 250 kbps, with minimum −85 dBm RF sensitivity essential and superlative transmission extent of 220 m.

The superlative transmission extent is calculated bearing in mind that, even though any legitimately suitable power is allowed, the "IEEE 802.15.4-compliant devices" ought to be capable of communicating and transmitting at −3 dBm. Giving, the energy efficiency challenges, short rate and short duty cycle are given. The "IEEE

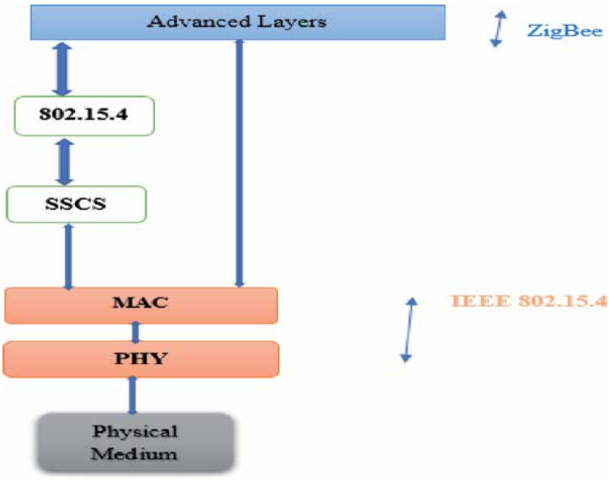

Figure 2.
ZigBee procedure stack.

802.15.4-compliant devices" are dynamic only during a brief period and the standard permits some devices to function with both the transmitter and the receiver inactive for about a duration of 99% [4].

3.2 The IEEE 802.15.4 MAC layer

The "IEEE 802.15.4" employs a procedure built on the CSMA/CA algorithm, which entails compensating attention to the channel before transmission for the reduction of the possibility of collisions with other continuing transmissions. The "IEEE 802.15.4" describes two diverse operational approaches, viz.; the "beacon-enabled (BE) and the non-beacon-enabled (nBE)," which correspond to two diverse channel access machineries.

The nBE approach nodes use an unpetitioned CSMA/CA procedure for the assessment of the channel and transmission of their packets [36]. The algorithm is executed by employing units of time (UT) known as "back off periods (BPs)." Foremost, each node will interrupt any actions for a haphazard number of BPs. Subsequent on this interruption, channel sensing is achieved for one UT. If the channel is discovered free, the node instantly starts the transmission; but if, in its place, the channel is busy the node enters again in the back off situation. There occur an uppermost number of times the node could attempt in accessing the channel. When this uppermost is attained, the algorithm ends and the transmission could hardly occur. According to reports from the EEE 802.15.4 Standard Part 15.4, in the BE mode (instead, the access to the channel is accomplished through a super frame [SF]), beginning with a packet, known as "beacon," transmitted by wireless PAN coordinator. The SF could contain an indolent portion, permitting nodes to go in sleeping mode, while the active portion is shared into two portions; "the contention access period (CAP) and the contention free period (CFP)," composed of what is known as the "guaranteed time slots (GTSs)," that could be allocated by the sink to precise nodes. However, the use of the GTSs is discretionary.

4. Applications of wireless sensor networks (WSNs)

According to Buratti et al. [4], the various conceivable applications of WSNs to every sectors globally is essentially boundless, from environmental monitoring and management [37], medical and health care services [38], as well as other aspects such as positioning and tracking [39], localization, logistic. Strappingly, it is imperative to emphasise that the benefits and applications affects the choice of the wireless machinery to be employed.

As soon as the requirements of the application are set, the network designers need to select and choose the machinery which allows the gratification of these requirements. Hence, the knowledge of the structures, benefits and difficulties of the various machineries is fundamental. As a result of the significance of the relationship between the requirements for application and the machineries, this section will attempt to briefly give an outline of the some of the utmost applications of WSNs.

As stated earlier, WSNs have gained substantial admiration as a result of their flexibility in resolving issues in different application fields and have all it takes to change our world in several diverse ways. Reportedly, WSNs have been efficaciously employed in several application domains [1–4, 7, 13, 26–29, 40–44] such as:

Military Applications: Possibly, WSNs is an essential fragment of military intelligence, facility, control, communications, computing, frontline surveillance, investigation and targeting systems.

Applications in Area Monitoring: In the aspect, the sensor nodes are positioned over an area where some display is to be observed. When the sensors notice the occurrence being observed (such as temperature, pressure etc), the occurrence is conveyed to one of the base stations (BSs), which then takes action appropriately.

Transportation Applications: Instantaneous traffic statistics is being composed by WSNs to later forage transportation models and keep the drivers on alert of possible congestion and traffic difficulties.

Medical/Health Applications: Some of the medical/health benefits of WSNs are in the areas of diagnostics, investigative, and drug administration as well as management, supporting interfaces for the incapacitated, integrated patient monitoring and management, tele-monitoring of human physiological information, and tracking and monitoring medical practitioners or patients inside the medical facility. According to Nwankwo et al. [45] nanoinformatics and nanomedicine are now beginning to advance in clinical applications via the use of biosensors.

Environmental Applications: The term "Environmental Sensor Networks (ESNs)" has developed to cover several benefits of WSNs to environmental and earth science study. This comprises of sensing oceans, seas, glaciers, atmosphere, volcanoes, forest, etc. However, there are presently some biosensors that have been developed for use in agricultural and environmental sustainability [29]. Some other key aspects are; air contamination monitoring and management, forest fires discovery/detection, greenhouse (GH) monitoring and management, and Landslide discovery/detection.

Structural Applications: WSNs can be employed for monitoring the movement of diverse structural projects such as buildings and other infrastructural projects like flyovers, bridges, roads, embankments, tunnels etc., allowing manufacturing/engineering practices to monitor possessions remotely without necessarily visiting the sites, and this would reduce expenses that would have been incurred from physical site visitations.

Industrial Applications: WSNs have been advanced for "Technological Condition-based Maintenance (TCBM)" since they could offer momentous cost reductions/investments and allow innovative functionalities. In wired classifications, the installation of adequate sensors is habitually limited by the amount involve in wiring.

Agricultural Applications: The employment of WSNs has been reported assist farmers in various aspects such as the maintenance of wiring in a problematic environment, irrigation mechanisation which aids more resourceful water use and reduction of wastes.

5. Design challenges in WSNs

Reportedly, there are several challenges placed by the disposition of sensor networks [1, 2, 7, 46–49], which are segment of those that are initiated in WSN systems. The sensor nodes interrelate over the wireless, lossy spots without substructure. Another projecting challenge is the one that is related to the constrained, customarily non-renewable natural resource; that is the energy basis of the sensor nodes. As reported by Akyildiz et al. [1, 2], so as to enjoy the complete benefit of the generation of the WSNs, the techniques need to be premeditated from the beginning with the aim of efficient monitoring and management of the natural resources (energy source).

According to Matin and Islam [7], the specific design challenges in WSNs are:

Scalability: SNs differ in scale from some nodes to possibly several numbers. Furthermore, the deployment density is correspondingly adjustable. In the process of gathering data with high resolution, the node density could reach the extent where a node has numerous neighbours in their range of transmission. The protocols positioned in SNs should to be scalable to these extents and should be able to maintain and preserve performance effectively.

Culpability Tolerance: SNs are susceptible and regularly deployed in hazardous environment. The failure in the nodes are supposedly due to hardware complications, physical impairment or through gruelling their energy source. Expectedly, the node failures are much higher than the one generally considered in strengthened or infrastructure-built WNs. The protocols positioned in a SN should be talented in detecting these failures in the nodes instantly and should be strongly robust in handling a comparatively huge quantities of the node failures while maintaining and preserving the complete functionality of the network system. This is particularly relevant to the routing protocol project, which ensure that alternative paths are accessible for redirecting of the packets. However, diverse deployment situations pose diverse culpability tolerance necessities.

Cost of Production: Due to several deployment models consider the SNs to be disposable devices, sensor networks could possibly contend with traditional information gathering methods only if the specific SNs could be produced economically. The target price intended for a NS should preferably be very low in price.

Hardware Limitations: At least, every NS needs to have a detecting component (sensing component), a processing component, a transmission component and a power source component. In some instant, the nodes could possibly have numerous built-in sensors or extra devices like a localization arrangement that assist the location-aware routing. Nevertheless, every extra functionality emanates with extra cost and amplifies the power consumption rate and physical dimensions of the node. Consequently, extra functionality needs to be continuously balanced in contrast to the cost and low-power requirements.

Topology of the Sensor Network: Even though WSNs have advanced in several aspects, the networks incessantly experience some constrained resources in terms of energy resources, computational power, storage (memory) and communications competences. Among all these aforementioned constrictions, energy resource is of utmost significance, and this is confirmed by the huge quantities of algorithms, procedures, and protocols that have been established for saving energy, and by this means encompass the generation of the network. Reportedly, maintenance of the topology is one of the utmost issues that could assist in the reduction of the energy consumption rates in WSNs [22].

The Media of Transmission: The communication and interaction among the nodes is ordinarily implemented by means of the radio communication over the prevalent ISM bands. Nevertheless, some sensor networks employ optical communication or infrared communication, with that of the infrared having the advantage of being strong and effectively free of interference.

The Consumption of Power: As previously stated, most of the challenges of WNSs mainly centred on the inadequate power resources. The magnitude of the nodes restricts the magnitude of the source of power (battery). Hence, in designing the both the software and hardware, there the needs to cautiously contemplate on the issues of resourceful energy use. For example, data compression could possibly reduce the quantity of energy used for radio transmission, but uses extra energy for the manipulation, computation or/and filtering. Also, the energy procedure depends on the application; where in some applications, it could be suitable to turn off a subdivision of nodes so as to preserve and conserve energy whereas other applications need all nodes to operate instantaneously.

According to Puccinelli and Haenggi [28], sensor networks offer an influential combination of disseminated sensing, computing and communication. They offer themselves to immeasurable applications and simultaneously offer several challenges as a result of their distinctiveness, essentially the rigorous energy limitations to which sensor networks are characteristically subjected. The distinguishing traits of sensor networks have a direct influence on the hardware design (HWD) of the nodes at least four levels namely; "power source, processor, communication hardware, and sensors." There are several HWD platforms that have been established in testing the innumerable ideas and concepts produced by various researchers and in implementing the applications to effectively suit all fields of study especially the scientific and technological aspects [50].

Presently, in the design and deployment of WSNs, several programming procedures have been projected, of which prominence are habitually on issues of low-level systems. Nevertheless, as stated earlier, for the simplification of the design and deployment of WSNs and abstract from technological LLB specifics, some HLB procedures have been anticipated, developed and established for its resolutions. According to BenSaleh et al. [3], applying the model-driven engineering (MDE) technique is becoming an auspicious solution in particular and these HLB procedures would be of great assistance in easing the design and deployment as well as mitigate some of the challenges of WSNs.

6. Conclusion

This chapter discusses some of the utmost issues of WSNs, ranging from applications to challenges on the technological points of view. Essentially, in designing a WSN it is required to describe the utmost appropriate technology to be employed and the communication procedures (such as signal processing, topology, approaches, etc). These selections are subject to various factors, and most significantly, the application necessities.

The first section of the chapter was keen in discussing the description of some of the limitations that should be fulfilled by the WSN and the various aspects that should be considered for designing a WSN. The proceeding section, was connected to the possibly authentic selections that could be completed, in terms of machineries. The purpose is to assist designer of WSNs in selecting or choosing of the utmost appropriate technology. The consideration was primarily focused on standard of the IEEE 802.15.4, for which also several possible performance levels are make available. Conclusively, it is suggested that a vision on imminent trends of research and prospects such as MDE techniques on WSNs should be put in place.

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Conflict of interest

There is no conflict to declare.

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Section 2

Design and Deployment

Chapter 3

Design Model and Deployment Fashion of Wireless Sensor Networks

Sana Akourmis, Youssef Fakhri and Moulay Driss Rahmani

Abstract

The ease deployment of Wireless sensor networks (WSNs) in the harsh and hard environment possesses a paved because the way it is. They are formed by sensor nodes which are responsible for examining environmental and corporal conditions to perform data processing. In this chapter, the manner of deployment will be presented, and how they communicate over a wireless link to unite the necessities of a specific application will be shown.

Keywords: WSN, system monitoring, connectivity, coverage, sensor node, routing protocol, path selection

1. Introduction

Wireless sensor networks considered as a special type of ad hoc network, where the fixed communication infrastructure and centralized administration are absent. Here, the nodes play both the role of hosts and routers [1, 2]. These Nodes can be deployed randomly or regularly in a WSN environment. There is a concession between these in terms of the number of nodes, deployment time, deployment cost, and feasibility of the placement scheme. They are smart and capable of accomplishing three complementary tasks: the reading of a physical quantity, the possible processing of this information, and the communication with other sensors [3]. Coverage guarantees the monitoring area is covered by at least one sensor node while connectivity is needed to make sure that every sensor node is precisely connected to the sink node or indirectly connected to the sink node by any other sensor nodes. In addition to their deployment fashion for an application, they form a wireless sensor network [4]. Its purpose is to monitor a geographic area, and sometimes to operate on it. Examples include a forest fire detector network, or abridging strength monitoring network after an earthquake [5, 6]. The network can include a large number of nodes (thousands). Though, their flexibility besides their ease deployment in unprotected environments, have allowed in improving people's living. Also, the capacity of the sensor on gathering information from surrounding is very helpful for a human being to make information accessible by the user [7]. In addition to their flexibility. Nowadays, they are also used in the construction of a smart home system. Moreover, Routing protocol

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design factors: network efficiency and lifetime greatly depend on the quality of the protocols used. So, routing in WSN must proceed to the formation of new routes between the nodes in case the failure of communication links [8, 9]. It turns out that, efficiency in energy consumption represents a significant performance factor that limits node capacity. They are limited in memory of their major constraint but cheaper. They have limited available power because there are depleting their energy in sense as well as in communicating the signal to the base station because communication needs more power than data processing [4, 10]. Therefore, computing [4, 8, 11] resources and batteries are more limited in sensor nodes than in ad hoc nodes. Indeed, to develop this system architecture, it is necessary to start from the high-level requirements for the realization of the requested application, then to the low-level hardware requirements. In this chapter, the focus is on the communication strategy about the Design model and deployment fashion of the wireless node. It is organized as follows: Section2 gives an overview of the wireless sensor network design system, the different sensor network elements are shown in Section3, Section4 explains the deployment model of nodes, Section5 presents the vulnerabilities and challenges in WSN. We will show many areas of application of the WSN in which they are used. And finally, the conclusion is provided in Section 7.

2. Wireless sensor network design system

2.1 Characteristics of a sensor network

A wireless sensor network is a relatively large set of nodes called sensors. These sensors are very small devices scattered a little randomly in an area called "sensing region" (see **Figure 1**). The sensors are autonomous and have the role of collecting information (varied according to the field of application) [6, 12]. These will then be sent to an administrator via the gateway (well node) using appropriate routing techniques which we will see in another part. The well or sink node is the intermediate node between the administrator who is generally very far away and the whole network.

Indeed, when a sensor has to inform the administrator of an event or simply send the information collected, it must first pass this information to the sink. It is the latter that will transfer the said information to the administrator through an extensive network such as the Internet or more simply via the satellite [2, 4, 10].

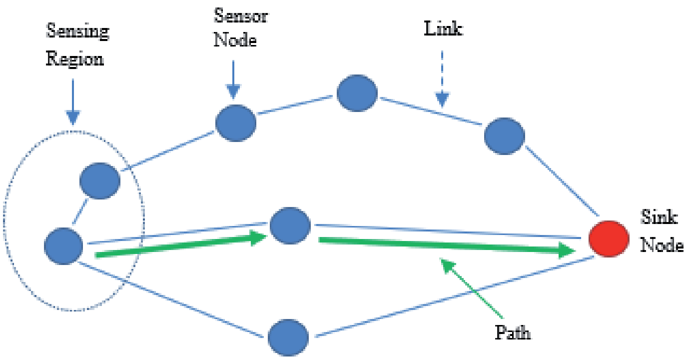


Figure 1.
WSN elements considered into the network.

Conversely, when it is now the administrator who wants to send information or requests to the various sensors of the 4th network or to one in particular, he too will have to go through the sink in order to reach his targets [13].

Thus, we have just seen that each sensor node will send its messages to the well node in order to inform the administrator [14]. However, it would be good to know that there are indeed two distinct types of communication architecture in a wireless sensor network. That are:

- The flat network

And

- The hierarchical network:

No particularity, the first hierarchical network is quite the simplest. All the sensor nodes have the same function and the same power except the well node which keeps its same function. it stipulates for the hierarchical network that the catchment area must be divided into several regions. Each region contains a number of normal sensor nodes added to these one or more nodes more powerful than the others. These sensors will act as a routing gateway between the different regions. This type of infrastructure makes it possible to offload the less powerful (and therefore less expensive) nodes of several network functions [13, 14].

So, we just saw the architecture of a wireless sensor network, defining the overall way of communication between the nodes and the administrator. But we still do not know how we go from an event to information sent to the user. In order to try to answer this, we can see below the hardware architecture of a deep sensor node.

The basic objectives of wireless sensor networks generally depend on the applications; however, the following tasks are common to several applications:

- Determine the values of some parameters according to a given situation. For example, in an environmental network, one can seek to know the temperature, the atmospheric pressure, the amount of sunlight, and the relative humidity in a number of sites, etc. [6].

- Detect the occurrence of events that we are interested in and it estimates the parameters of the events detected. In traffic control networks, one may want to detect the movement of vehicles through an intersection and estimate the speed and the direction of the vehicle [15].

- Classify the object detected, e. g in a traffic network is a vehicle a car, a bus, etc. [12, 15].

In general, WSN is formed by sensor nodes. It is responsible for examining environmental and corporal conditions to perform data processing. It is considered as a special type of ad hoc network where the fixed communication infrastructure and centralized administration are absent routers [16]. The sensor nodes form a network of sensors and the nodes play both; the role of hosts, and they are smart. Sensors are capable of accomplishing three complementary tasks: the reading of a physical quantity, the possible processing of this information, and the communication with other sensors. They are deployed to accomplish an application. Typically, they can be rapidly deployed and distributed over a geographical area in a multi-hop packet radio communication network without the help of an established infrastructure as it is shown in **Figure 2**.

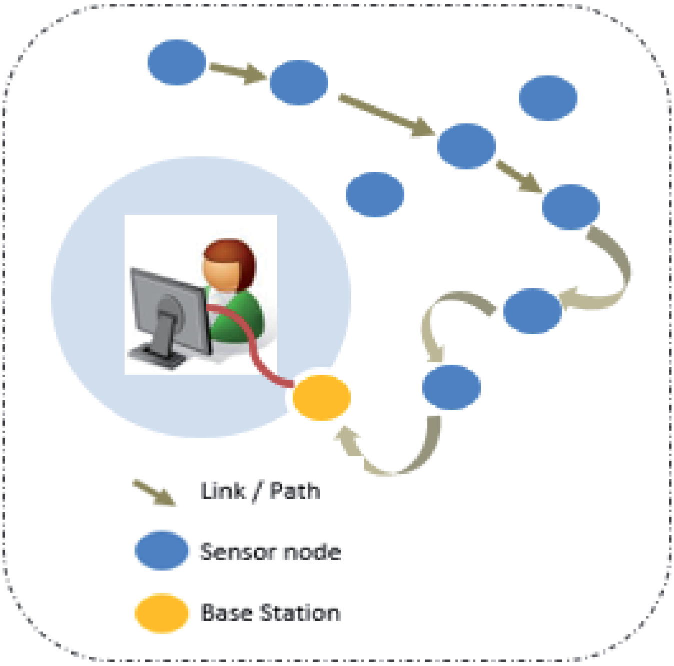


Figure 2.
WSN architecture [6, 17, 18].

Since wireless sensor nodes are usually very small electronic devices. It has been considered as a special type of ad hoc network. It brings an interesting perspective (**Figure 3**). This kind of network is capable of self-configuring and self-managing without the need for intervention human. One of the main design objectives of the WSNs is realizing communication data while trying to extend the lifetime of the network and prevent the degradation of connectivity by using energy management techniques. Low energy nodes are used to perform detection in the area of interest. However, wireless transmission is a significant simplification that can avoid a lot of wiring. Its main advantage is the capacity for self-managing and self-configuring without the need for human intervention. The nodes cooperate and communicate

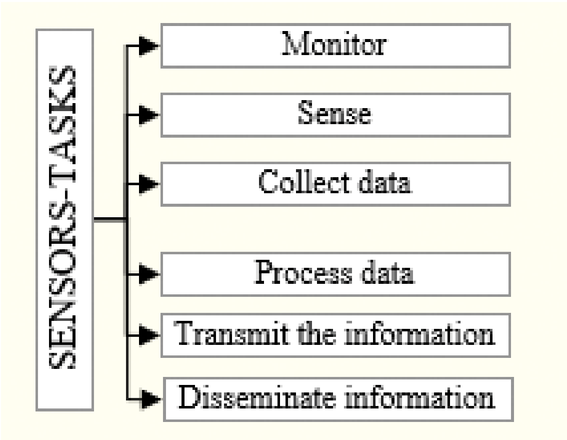


Figure 3.
Sensors-tasks [3–5, 7].

with each other to transmit the data to each other in the WSN network as seen in **Figure 1**. Hence, these two communicative nodes as shown in the same figure (**Figure 1**) are called a one-hop neighbor.

Thus, we have just seen that each sensor node will send its messages to the well-Known Base station as expected in WSN architecture we must have one destination.

In order to inform the administrator or the end user. However, it would be good to know that there are indeed two distinct types of communication architecture in a wireless sensor network. There are two types in WSN (Flat and Hierarchical architecture) that we will see in the next section.

2.2 Path selection in WSN

These sensors nodes determine the route/path by routing packets using various routing protocols [2, 9]. Nodes of the WSN network maintain connectivity in a distributed way. This topology instability needs a routing protocol to be run in each node to create and maintain routes between nodes. One of the main design objectives of the WSNs is to realize communication data while trying to extend the lifetime of the network and prevent the degradation of connectivity by using energy management techniques [8, 18]. The Designing security protocols require understanding these limits (sensors in terms of energy, memory, computing capacity) and achieving acceptable performance with security measures to meet the needs of an application. The design of security protocols requires understanding these limits of WSNs and achieving acceptable performance with security measures to meet the needs of an application [12, 13, 15]. Preferentially, the node should be able to enter and leave the network even if the design, implementation, and configuration are correct, resource depletion is possible. This is why WSNs are classified into infrastructure-less networks. Moreover, their ease deployment in the harsh and hard environment possesses a paved to the way for it. Their capacity on gathering information from surrounding is very helpful to improve the quality of living, as it makes life easy because of modern technology in our daily life [4, 10, 11]. The manner of deployment of WSN will be presented in this chapter, and how they are communicated over a wireless link to unite the necessities of a specific application that will be shown. There are a lot of factors that are included the organization of wireless sensor networks that are: network organization, number of nodes, number of routers, network topology, and geographical distribution [8, 18]. They have been recently attracted a lot of interest in the research community due to their wide range of applications. In this way, we can choose any kind of sensors to be used for a specific purpose such logistics, smart agriculture, industrial controls, smart home, military target tracking, and security monitoring. This chapter will describe the design, deployment, and applications in WSN [18, 19].

2.3 Difference between sensor and ad hoc network

Nowadays, Wireless technologies have been developed rapidly, and Wireless sensor networks (WSNs) are one of them [2, 4]. A deployment of several devices equipped with sensors and it has been considered as a special type of ad hoc network that brings an interesting perspective. It can be rapidly deployed by a set of wireless computers in a multi-hop packet radio communication network without the help of established infrastructure [14, 16]. Or, it can only be equipped with limited power and wireless sensor nodes can perform a collaborative measurement process. In this network, the use of wireless transmission in the open-air medium remains the most important thing to make information accessible for the user. In brief, Wireless ad-hoc networks can be used in special areas where wired network infrastructure may be unsuitable. (Or a wired network infrastructure may not be suitable for reasons such as cost or convenience [3].

In ad hoc mobile networks (MANETS) the nodes usually cooperate and transmit packets to each other to allow communication out of range (out of range). The nodes in WSNs rely on other nodes to transfer their packets [5]. The difference between both Wireless sensor network and Ad hoc network in the following:

- The density of deployed nodes is much higher in sensor networks
- The sensor nodes have limited capacity in energy and memory
- The topology in sensor networks is often dynamic.
- Communication between the nodes is by diffusion and not point to point in a network of sensors.
- Sensors may not have a global identifier due to a large number of nodes.

3. The different sensor network elements

Recent findings on empirical studies have deduced that radio links between low-power sensing devices are far from being reliable. This why making a model that is akin to the reality of radio communication channels is something out of reach or at least very challenging [2, 8]. Computing nodes (usually wireless) in an ad hoc network act as routers to deliver messages between nodes that are not within their wireless communication range [1, 7]. Because of this unique capability, mobile ad hoc networks are envisioned in many critical applications (e.g., in battlefields). Therefore, these critical ad hoc networks should be sufficiently protected to achieve confidentiality, integrity, and availability. Wireless sensors are typically low-power, low-cost, and short-range minuscule devices. Multi routes rely on data from the monitored region to the sink. The measuring nodes are a wireless device, they usually cooperate and transmit packets to each other to allow communication out of range, they rely on other nodes to transfer their packets. Preferentially, the node should be able to enter and leave the network [12, 13]. The self-organizing capability makes them flexible for communication in areas [6].

But in fact, resource depletion is possible even if the design, implementation, and configuration are correct [15]. Or, it can only be equipped with limited power. In WSN. The nodes usually cooperate and transmit packets to each other to allow communication out of range [18]. That's why Multi-hop routes are needed to transfer data from node to another in the network. The tasks that the sensors can perform are shown in **Figure 1**. Every single node in the network must be able to perform these different tasks. Every single node should be made to give a set of basic primitives to combine the interconnected web that will appear as they are scattered. Since sensor nodes are: -small distributed, they may be on a large scale or in a dangerous area [8, 19]. Their battery is small and it maybe not recharged or replaced. So, the network lifetime is prolonged when the battery energy is used wisely. Individual nodes interact with the environment in which they are scattered to perform the functions dictated by the sensor network applications [1, 4, 11]. They focus on interaction with the environment instead of focusing on interaction with humans [10]. So, it can be said that in the hardware architecture of the wireless sensor network has four basic subsystems of sensor nodes:

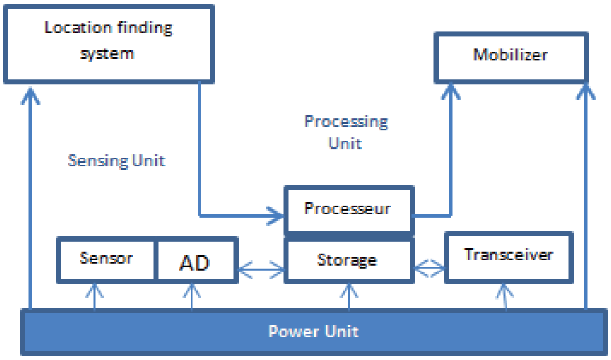


Figure 4.
Sensing node design [5, 6, 14, 17].

- Computing subsystem
- Power subsystem
- Sensing subsystem
- Communication subsystem

Concerning software architecture, a wireless sensor is a device consisting of a data acquisition unit using a sensor of a physical quantity + (processing) + transmission by wireless technology. A wireless sensor network is a set of sensors grouped within the same wireless network [12, 14]. They are considered as a special type of ad-hoc network composed of "nodes." These nodes form a catchment field and routing that is using routing protocols which are in star or hybrid form, to an end-user which is the sink it is finally a user request. They have limited available power because there are depleting their energy in sense as well as in communicating the signal to the base station Therefore, computing resources and batteries are more limited in sensor nodes than in ad hoc nodes. A standard sensor type-TelosB has a 16-bit, 8 MHz RISC CPU with 10 K RAM, 1024 K flash storage and 48 K program memory [13–15]. The general overall software architecture of the sensor net is shown in **Figure 4**.

4. Architecture of a sensor node

Advances in miniaturization have enabled sensors to integrate several modules despite their relatively small size. They mainly consist four (4) units [14, 17, 18]:

- A collection unit
- A processing unit
- A transmission unit
- An energy management unit

In addition to these, we can find depending on the field of application of the sensor network, a unit for localization, the unit for movement, and sometimes the unit for producing energy thanks to small solar panels. The diagram in **Figure 4** shows all of these different modules. In our case, let us dwell on each of these modules in more detail [5, 6, 9, 14].

- Captive Unit: it is the module for which wireless sensors have been developed. It breaks down itself into two subunits. The “sensor” or receiver will recognize the event to be monitored by the sensor. Then, it will perceive the analog signals emitted by the receiver to transform them into a digital signal understandable by the processing unit.

- The Processing Unit: Consisting of a processor, and sometimes even a small storage memory operates using an operating system specially designed for this type of medium (for example: open source TinyOS). This unit executes communication protocols by allowing the node to collaborate with the rest of the network. Under certain conditions, the processing unit can analyze the observed data in order to reduce the task at the well node.

- The Transceiver Unit: it takes care of the operations on the transmission and reception of data. This emission is either optical or the radio-frequency type.

- The Power Unit: being the major constraint of this technology, it was necessary to insert a module within the sensors allowing sparse management of the energy in the sensor. Therefore, it will be responsible for distributing the energy available in the sensor optimally; for example, by putting inactive components on standby. It will also be responsible for managing the energy recharging system, but it provided that a module for this purpose.

- Location Finding System: it provides the location information required by certain routing protocols. Usually, it is a Global Positioning System (GPS).

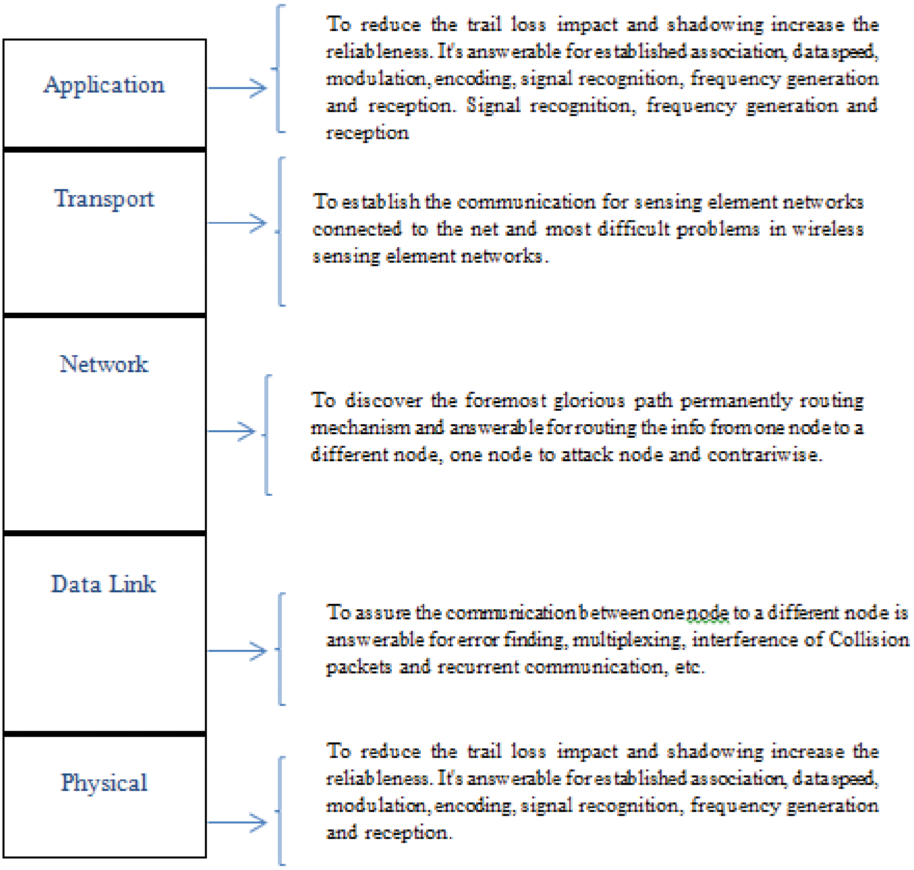
- Mobilizer: in the case, certain larger sensors are possible to move them. This system what will have the task assigned to it. The different components of the sensor node described above define its possibilities. In other words, they let you know what a sensor is capable of doing and how far it can do it. It brings us to our next point.

5. Deployment model of nodes

Wireless transmission is an important factor that allowed WSN to deploy successfully. It has been increased in recent years and has been appeared even in smart house systems [1, 2]. Many communication technologies, such as IrDA, Bluetooth, and Zigbee, GSM/GPRS (General Packet Radio Service), PSTN (Public Switched Telephone Network), etc. have been developed for different locations [16, 18]. A kind of real-time system in which multiple sensors connected simultaneously to one gateway unit it become indispensable, and they are transformed into wireless sensor networks (WSNs) [10]. A mobile sensor sends data to the nearest sensor which is transferred later to the BS via the shortest path as it is shown in **Figure 2**. Indeed, when a sensor has to inform the administrator of an event or simply send the information collected, it must first pass this information to the sink (see. **Figure 2**). It is the one that will transfer the understood information to the administrator through an extensive network such as the Internet or more simply via the satellite. Conversely, when the administrator wants to send information or requests to the various sensors of the network or one, in particular, the two will have to go through the sink to reach its targets [4, 11].

It turns out that the use of these technologies makes information more accessible by the user. This would significantly improve people's living quality. Especially that wired network has some problems, such as inconvenience and high cost, unsatisfactory security assurance [2]. Therefore, their concept in sensing with their capabilities in transferring the data into a signal has paved the way for the creation of a lot of potential applications that we will see later in this chapter.

The routing algorithm is used to accomplish this task to support multi-hop communication inside the network by the nodes [9]. So, we will understand how to communicate this data and how to monitor the information shared between nodes. These data are typically relayed from node to another and these links are dynamically built on -demand (reactive routing) or dynamically re-computed (proactive-routing) [3, 12]. Proactive routing protocol: they are presented on the same routing principle as wired networks. The routes in this type of routing are calculated in advance - each node encountered updates several routing tables by exchanging packets between neighbors. Also, they luckily tend to have a communication brink between them for reason that path computation is generated upon request or the occurrence of specific events from the application data to the sink node. Preferentially, the node should be able to enter and leave the network [1].



Application	To reduce the trail loss impact and shadowing increase the reliableness. It's answerable for established association, data speed, modulation, encoding, signal recognition, frequency generation and reception. Signal recognition, frequency generation and reception
Transport	To establish the communication for sensing element networks connected to the net and most difficult problems in wireless sensing element networks.
Network	To discover the foremost glorious path permanently routing mechanism and answerable for routing the info from one node to a different node, one node to attack node and contrariwise.
Data Link	To assure the communication between one node to a different node is answerable for error finding, multiplexing, interference of Collision packets and recurrent communication, etc.
Physical	To reduce the trail loss impact and shadowing increase the reliableness. It's answerable for established association, data speed, modulation, encoding, signal recognition, frequency generation and reception.

Figure 5.
OSI MODEL and their signification [4, 8, 10, 18].

We can use any kind of protocol to communicate the information, and careful protocol design is needed as well as a successful target application [4, 8, 10]. So, the routes are determined before they are used. Since host nodes are mobile. So, it causes frequent and unpredictable topological changes in the network [17]. Dealing with the formation and maintenance of WSN Network is very difficult. In recent years, a lot of routing protocols have been proposed for WSNs, out of two major protocols AODV which is a reactive routing protocol because its uses and efficiency in energy consumption represents a significant performance factor that limits node capacity [8, 11].

Also, each layer of the model communicates with an adjacent layer (that of the top or that of the lower part). Each layer uses the services of the sub-bases and provides some to that of higher level.

As it was mentioned above each layer has its own significant. And to give more detail (see **Figure 5**).

6. Vulnerabilities and challenges in WSN

Wireless sensor network is an interconnection among hundreds, thousands, or millions of sensor nodes. It is capable of sensing, data processing, and communication tasks. During this process, Maintenance and route computation are needed to involve a minimum number of nodes [20].

So, their flexibility is provided by each node which acts as a router to forward each other's packets to enable out of range communication and to forward each other the data packets which is multi-hop; because Their less capable hardware and limited capability such as node limitation, network limitations, physical limitations, the inherent vulnerabilities of wireless communication like physical vulnerability and other related to wireless technology, also, the dense deployment nature in public and hostile environments in many applications, the restricted field of sensing and sensitive nature of collected data, unattended operation [4, 11].

This minimal configuration and lack of infrastructure, also the quick deployment makes WSNs convenient for emergency operations especially for military operations [2, 5]. In WSN, multi-hop routing, higher latency in packet transmission may achieve difficult synchronization which is due to network congestion and processing intermediate nodes.

Being limited by computation resources, WSN process the following limitations as it is shown in **Figure 6** because the position of the sensor nodes in a wireless sensor network (WSN) is of paramount importance for their design and for their implementation that will intersect with their architecture and design requirements in parallel with their specifications techniques like energy consumption, connectivity and coverage. Let us started with the first metric which is the coverage.

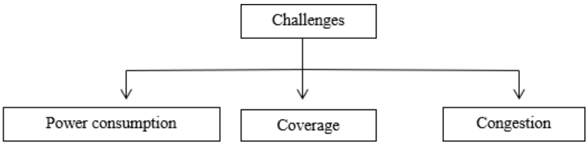


Figure 6.
WSN challenges [1, 3, 7, 8, 18, 19].

6.1 Coverage

Coverage ensures the monitoring area by at least one sensor node while connectivity is required to make sure that every sensor node is directly connected to the sink node or indirectly connected to this last via any other sensor nodes [1, 11, 19]. Two sensor nodes that are outside the communicate directly [11, 19]. Consequently, connectivity cannot be guaranteed. Most applications in WSNs involve battery-powered nodes with limited energy where their batteries may not be convenient for recharging or replacing [7]. Thus, it is very crucial to find a way to reduce the energy consumption because it is inconvenient to keep on changing the battery specially if WSN is installed in remote area. The desired coverage can be assured as the locations of sensor nodes are carefully planned according to certain requirements. A wireless sensor network (WSN) has to maintain a desirable sensing coverage and periodically report sensed data to the administrative center (i.e., base station), and the reporting period may range from months to years.

Coverage and lifetime are two paramount problems in a WSN due to constraint of associated battery power [5]. All the existing theoretical analyses on the coverage and lifetime are primarily focused on the random uniform distribution of sensors or some specific network scenarios (e.g., a controllable WSN) [11, 18].

6.2 Connectivity

Coverage and connectivity can be optimized by deploying a large number of sensor nodes. Unfortunately, the connectivity cannot remain unchanging at any working time. The sensor network is a broadcast network in which any signal can be captured by adversaries at any time. These features make wireless ad-hoc sensor networks more vulnerable than wired networks. This presents real challenges in the implementation of the following security requirements for WSNs [4, 11, 19].

6.3 Energy consumption

This factor is of paramount importance during the design and implementation of WSN network which ensure the network lifetime in its operating system.

Another concern in WSN, is about energy efficiency. In WSN, each sensor node may need to support multiple communication models including unicast, multicast, and broadcast. Therefore, due to the limited battery lifetime, security mechanisms for sensor networks must be energy efficient [1, 10]. Especially, the number of message transmissions and the amount of expensive computation should be a few as possible [17, 19].

Since the transmission distance also affects the energy consumption, it is another factor to be considered [8]. Due to these factors, a sensor node placement algorithm for WSN is needed to ensure that the position of deployed sensor nodes is able to provide maximum coverage, minimum energy without jeopardizing connectivity although the communication methods and protocols of the sensor node may affect the coverage, connectivity and energy consumption, they are only considered after the sensor node positions have been determined [4, 19]. Romoozi [16] stated that these is a tradeoff between energy consumption and network coverage. Bigger coverage is achieved if the distance between two sensor nodes is further [16]. However, their energy consumption will be higher due to longer distance data transmission. The tradeoff between system lifetime and system reliability is a paramount design consideration for wireless sensor networks [2, 4, 11].

Constraint	Description
Energy constraints	Smaller memory capacity Limited battery life
Memory limitations	Limited memory capacity Processing power Low computational power Low bandwidth
Unreliable communication	Open air medium Wireless transmission
Higher latency in communication	Limited radio spectrum Affects multiple access, interference
Node limitations	Frequent path beak
Physical limitations	Lack of tamper resistant packaging No centralized infrastructure Design constraint
Heterogeneous nature of sensor nodes	Limited battery power Inherent limitations in sensor networks

Table 1.
Nodes' constraints in WSN [1, 3, 7, 8, 12, 19].

Due to distributed nature of these networks and their deployment in remote areas, the node constraints have been summarized in **Table 1**.

They are fully distributed, and adaptive regarding frequent changes [2]. Their deployment in ubiquitous and pervasive applications, inherently; a wireless sensor network is an interconnection among hundreds, thousands or millions of sensor nodes. Sensor node is capable of sensing, data processing and communication tasks. During this process, Maintenance and route computation are needed to involve minimum number of nodes [4].

7. Areas of application of the WSN

The basic objectives of wireless sensor networks generally depend on the applications; however, the following tasks are common to several applications.

They have a large catalog of applications where they can be found. We have already mentioned a few that shows just a range of possibilities. Among them, we can try to name few [5–7, 11, 13, 15, 20] in where they can determine the values of some parameters according to a given situation. For example, in an environmental network, one can seek to know the temperature, the atmospheric pressure, the amount of sunlight, and the relative humidity in a number of sites, etc. [12, 17].

Detect the occurrence of events that we are interested in and it estimates the parameters of the events detected. In traffic control networks, one may want to detect the movement of vehicles through an intersection and estimate the speed and the direction of the vehicle [5, 12]. Classify the object detected, e. g in a traffic network is a vehicle a car, a bus, etc. [6]. So, they are fully distributed and adaptive regarding frequent changes. Their deployment in ubiquitous and pervasive applications,

The ease of deployment of wireless sensor networks (WSN) in a harsh and hostile environment has paved the way for the use of several applications.

Wireless Sensor Networks (WSNs) have recently attracted a lot of interest in the research community due to their wide range of applications and have a vast area of application for real-time event detection. Their simplification in wiring and harness helps in improving people's living quality. They are implicated in smart homes in these last years. Some applications already exist using WSN especially in the following fields [6, 12, 14, 16–18]:

Mission-critical applications in wireless sensor networks (WSN) such as fire alarms, radiation leaks, and monitoring in hostile environments should have a fast, reliable, and tolerant response to protocol failures routing. Otherwise, these applications will not be able to function properly and it will bring unexpected material, financial or human losses [2, 9, 11].

Using the miniaturization of micro-sensors, the increasingly low cost, the wide range of types of sensors available (thermal, optical, vibration, etc.) as well as the wireless communication medium allow the application of sensors in several fields including:

In **the Military sector** as in many other technologies, the military sector was the initial engine for the development of sensor networks. The rapid deployment, the reduced cost, the self-organization, and the fault tolerance of sensor networks are characteristics that make this type of network an appreciable tool in such a field. Currently, WSNs can be an integral part of a command, control, communication, surveillance, reconnaissance, etc. [2, 16].

The Medical field, Sensor networks are widely used in the medical field. This class includes applications such as: providing a help interface for the disabled, collecting better human physiological information, as well as, facilitating the diagnosis of certain diseases, continuously monitoring the sick and doctors inside the hospital. Also, they can be used to ensure permanent monitoring of the vital organs of human beings thanks to micro-sensors which can be swallowed or implanted on the patient (blood sugar monitoring, cancer detection, ...). They can also facilitate the diagnosis of some diseases by carrying out physiological measurements such as: blood pressure, heartbeat, temperature. Each sensor must have a very specific task for using it. It is mainly a remote monitoring of a patient [12, 16].

The Architectural domain Transformation of buildings into intelligent environments is capable of recognizing people, interpreting their actions, and reacting to them [12, 14].

The commercial domain is among domains where sensor networks have proven their usefulness. Several applications can be listed in this sector, such as: monitoring the condition of the equipment, controlling and automating the machining processes, etc. [7, 13, 14].

The environmental field is fairly varied field. The sensors are used to detect the pollution level of factories as well as to monitor the activity of a volcano. For example, we can mention the real-time detection of forest fires and faster industrial risks and reduce the leakage of toxic products (gas, chemicals, radioactive elements, petroleum, etc.). to detect natural disasters (forest fires, earthquakes, etc.). It detects fumes of toxic products (gases, chemicals, petroleum, etc.) in industrial sites such as nuclear or oil plants [12, 15, 17].

The security domain is the most important and sensitive area or sector in which the sensors can be in buildings in order to detect alterations in their structure or else be used to detect intrusions by building a distributed alarm system, monitoring railways, to prevent accidents, or the detection of water leaks in dams to avoid possible damage [2, 9, 12].

8. Conclusion

Wireless sensor networks have the potential for many applications (military, security, environment, medicine, commerce, etc.). The choice and model of a WSN depends greatly on the need for the application as well as the type of sensors used. In this chapter, we had the opportunity to discover what is a WSN, and the elements that go with it to lead an application to a specific domain. The advance of technology allowed the creation of prototype WSNs, but the hardware and software both have a way to go before WSNs are cost-effective, practical, and useful. To sum up, it emerged from this first chapter that thanks to their small size, their relatively low cost and their various functional characteristics, sensor networks offer us a truly immense range of possibilities. They can be used both on a civil level and in specialized fields. Unfortunately, the various constraints mentioned still hamper in their use. Indeed, the amount of energy is a big brake on this technology which continues fortunately to develop. On the other hand, another concern in this technology is the assurance of the conduct of information. So, the assurance as a captured phenomenon has been transmitted to the administrator. In this regard, the requirement for the security of its wireless sensor networks is one of the main obstacles. Securing a network of sensors amounts set up the various security services in this network, while taking into account its different characteristics. More precisely, it is to secure the routing protocols of the network layer; and it will be the main point of another next chapter.

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Chapter 4

An Algorithmic Approach to the Node Selection Problem in Industrial Wireless Sensor Networks

Veeramani Sonai and Indira Bharathi

Abstract

Industrial Wireless Sensor Networks (IWSN) are the special class of WSN where it faces many challenges like improving process efficiency and meet the financial requirement of the industry. Most of the IWSNs contains a large number of sensor nodes over the deployment field. Due to lack of predetermined network infrastructure demands, IWSNs to deploy a minimum number of sink nodes and maintain network connectivity with other sensor nodes. Capacitated Sink Node Placement Problem (CSNPP) finds its application in the Industrial wireless sensor network (IWSN), for the appropriate placement of sink nodes. The problem of placing a minimum number of sink nodes in a weighted topology such that each sink node should have a maximum number of sensor nodes within the given capacity is known as Capacitated Sink Node Placement Problem. This chapter proposes a heuristic based approach to solve Capacitated Sink Node Placement Problem.

Keywords: industrial wireless sensor networks, sink node, capacitated sink node, node placement, wighted topology

1. Introduction

Traditionally, the industries are automating their system using wired communications. The wired communication requires quite expensive communication channels and also it needs to be monitored regularly. Due to the high cost incurred in maintaining the wired system, most of the industries not implementing it. Therefore, cost-effective and alternative to wired system needs to be implemented in the industries. Due to recent growth of wireless sensor network (WSN), demands improvement of product development and service provisioning process for the industrial applications. Due to recent enhancement in the wireless sensor network (WSN), the realization of industrial automation can be feasible using WSN. **Figure 1** shows a simple structure of wireless sensor network. In WSN, a small sensor unit is attached to every industrial equipment to monitor the environmental parameters like humidity, temperature, pressure etc., Since all the nodes are not actively participating in the data collection process only some the nodes will be used to gather the data from different sources and these nodes are known as *sink node*. This measured information is transmitted to the sink node and the to the common

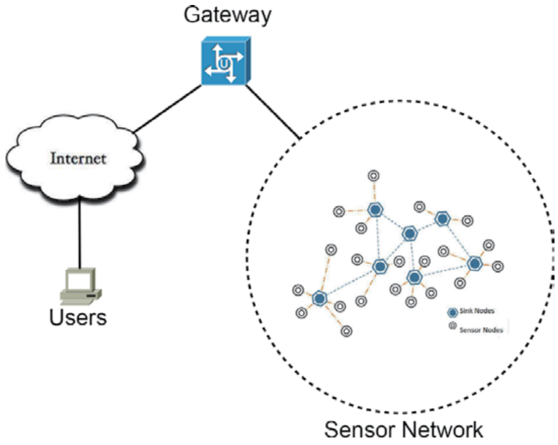


Figure 1.
Simple wireless sensor network.

gateway. Finally, the data will be sent the users through Internet where gateway is connected. In this regard, WSN is widely used to create industrial wireless sensor network (IWSN) that rapidly responses to the real-time events.

Recently, there are many research activities mainly focusing on developing a method to address the challenges like Quality-of-Service (QoS [1, 2]), data redundancy, resource constraints, security, large-scale deployment in the IWSN. In a large-scale network, having single sink node has some disadvantages related to performance and scalability. In such case, the amount of sink nodes in the network has to be increased to overwhelm sink node failure. Hence a better solution for this problem is the usage of multiple sink nodes. Most of the researches are also not focused on the task of multiple sink nodes in the sensor network. So in this chapter, we are concentrated on deploying and handling multiple node in the sensor network.

The sink node deployment problem impacts in flow *set-up time, fault tolerance* and *reliability*. These issues include deployment of sink nodes in the specified topology and decide the minimum number of sink nodes required for the same topology. Each node in the topology is connected with weight value known as capacity and each edge is said to be connected with weight value called processing request to the sensor. Deployment of least number of sink node in a specified network topology *will reduce the sink nodes and interaction time between the sensor nodes become* an NP-Hard problem [3]. Thus defining the optimal number of sink nodes is a challenging problem in the Industrial Wireless Sensor Networks (IWSN) because this affects many metrics in the network. In early, sink node placement problems use interaction time between the sensor node and the sink node as metric for each sink node. Those approaches do not consider the situation when the sink node failure happens. So, each sink node has been assigned a maximum (request processing) load apart from considering interaction time. The load applied to process the real-time actions determine the availability as well as the efficiency of the network. Hence the sink node offer the satisfactory resources to implement such actions. The load for the sink node is considered based on the number of actions arrived. Due to insufficient capacity of sink node, to manage resources like processor, bandwidth and memory. In this chapter, the sink node is defined as capacitated which denotes the maximum number of actions are to be processed by the sink node. While choosing the sink node to control different sensor node, the communication time among sensor node and sink node should be reduced in case, if the nodes are said to be near to each other. If both sensor and sink node are far away, then it takes more time to interact with one another. The core objectives of load consideration for every sink node are as follows:

- Every sensor node has a restriction on memory and processing of each action, only limited number of requests are processed by the sink node.
- As the load of the sink node increases, it fails to handle the request more than its maximum capacity. This will leads to increase of sink node and sensor interaction time.
- If single sink node fails then it may affect another sink node.

The sink node and sensor node communication time plays an essential parameter in the deployment of sink node. A simple approach is, the sensor node is said to be connected with the nearest selected sink node. But this method fails to work properly due to the limitation of load on each sink node. To overcome this issue, the sensor node connecting to the sink node should be stopped as long as it maximum load is reached. The main objective here is to place a minimum number of sink node in the network. This work also focused on reducing the interaction time between sink node and sensor node. This work proposes an efficient heuristic method to resolve Capacitated Sink Node Placement Problem.

2. Literature survey

IWSNs brings several advantages over wired industrial automation like monitoring and control [4–6]. In order to utilize the benefits of IWSNs, effective communication system needs to be maintained. Such system should address the unique challenges in the IWSNs. In this regard, many researchers working hard to find the solution to the IWSNs challenges especially establishing and maintaining network connectivity. In a large-scale network, identifying the minimum number of sink nodes and its appropriate placement becomes NP-Hard problem [3, 7–12].

3. Problem statement

3.1 Prefaces

Assume a simple connected topology be T with non-empty node of set $V(T)$ and the edge set be $E(T)= \{\{u,v\} \mid u,v \in V(T)$ and u is adjacent to v in T and $u \neq v\}$.The *neighborhood* of a node v of T, $N_T(v)$, is the set of vertices adjacent to v in T. The degree of the vertex v is $d_T(v) = |N_T(v)|$. $\Delta(T)$ denotes the maximum degree of a topology T.

3.2 Problem description

Capacitated Sink Node Placement Problem (CSNPP) is defined as follows:

Given a weighted topology T with weighted nodes $V(T) = \{v_1, \dots, v_n\}$, and the weighted edges $E(T)$. Here, the objective is to find $S \subseteq \{v_1, \dots, v_n\}$ such that $|S|$ is minimum and for each node in S, say x, covers the maximum subset $R \subseteq N_T(x)$ subject to the constraint given in Eq. (1),

$$\sum_{y \in R} weight(x,y) \leq weight(x) \quad (1)$$

where, $weight(x)$ denotes the weight of the node x and $weight(x,y)$ denotes the weight of the edge between x and y.

3.3 The solution for the capacitated sink node placement problem (CSNPP)

The node placement problem in the network becomes NP-hard [3]. An efficient heuristic method is applied to provide a solution to this problem. The proposed method implements a novel algorithm with the time complexity of $O(n \log n + n\Delta \log \Delta)$, where n is the number of nodes and Δ is the maximum degree of the topology T.This method choose the node that had maximum node weight value and started assigning the neighborhood nodes with its associated edge weight. Once the sum of edge weight value is larger than the node weight value, then the node is terminated. Furthermore this method does not consider the maximum degree of a node. The sorted nodes are find first and unmarked the rest of the nodes in topology T. Then, for every unmarked node x in the sorted node list, this algorithm requests one more algorithm 1, which allocate sensor node for node x. Next process, the node is marked as x and all nodes assigned to it, and finally node x is added to the necessary set of sink nodes. This step is repeated until all the nodes are marked. The performance measures to the Node_Assignment(W, S, N), where W denote the maximum capacity of the node, S denote the set of weighted edge value incident on a node, and N represents set of nodes connected with those node. The new node assignment procedure is described in Algorithm 1.

Algorithm 1 Node_Assignment(W, S, N).

```
Require: Consider a set $N$ consists of $m$ weighted nodes, say $n_1, n_2, \ldots, n_m$ and a set
         $S$ of $m$ weighted edges, say $e_1, e_2, \ldots, e_m$ and the maximum capacity $W$.
Ensure: The set $M \subseteq N$ such that $|M|$ is maximum subject to the constraint

         $\sum_{n_i \in M} e_i \leq W$

         Let $M = 0$.
         Sort the edge weights in increasing order, say $e_1 \leq e_2, \ldots, \leq e_m$.
         for $i = 1$ to $m$ do.
           if $\sum_{j=1}^{i} e_j \leq W$ when.
             $M = M \cup \{n_i\}$ $M$
           end if.
         end for.
         return $M$.
```

Algorithm 2 Placing_Sink_Nodes.

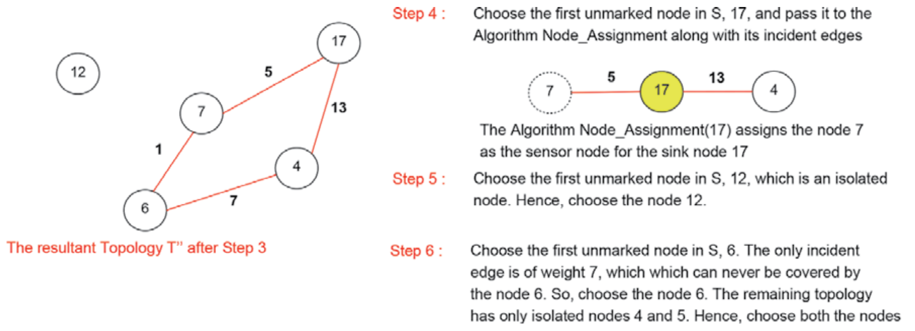
```
Require: The weighted topology $T$ with weighted nodes.
Ensure: Subset of $V(T)$ to be placed as sink node.
Let $T$ has $n$ weighted nodes.
Sort the weights of nodes in decreasing order, say $w_1 \leq \ldots \leq w_n$. Let $v_1, \ldots, v_n$ be
the corresponding labels of the nodes.
```

```
Let $e_{ij}$ denotes the weight of the edge $\{v_i, v_j\}$.
Unmark all the nodes $v_i, 1 \le v_i \le n$.
for $i = 0$ to $n$ do.
    if $v_i$ is unmarked then.
        Let $S = \{e_{ij} | v_j \in N_T(v_i) \text{and} v_j \text{isunmarked}\}$. Let $N$ be the set of nodes associated to the $v_j$'s in $S$.
        $Node\_Assignment(w_i, S, N)$.
        Mark $v_i$ and mark the nodes assigned to $v_i$.
    end if.
end for.
```

---

4. Illustration of the proposed capacitated sink node placement problem

Algorithm 2 is traced as follows by using the topology T as shown in **Figure 2**. The node with weight value 21 has the highest degree so it is chosen for locating the initial sink node. This first node then occupy its neighborhood nodes with weighted values 19, 11, 13 since sum of its edge weight value is fewer than or equal to node with value 21 $(15 < 21)$ as given in **Figure 3**. Likewise, the next node with higher weight value is 20 and it can occupy it neighborhood nodes 16, 8, 9 since the summation of edge value is smaller $(14 < 20)$ as shown in **Figure 4**, which illustrates



The resultant Topology T'' after Step 3

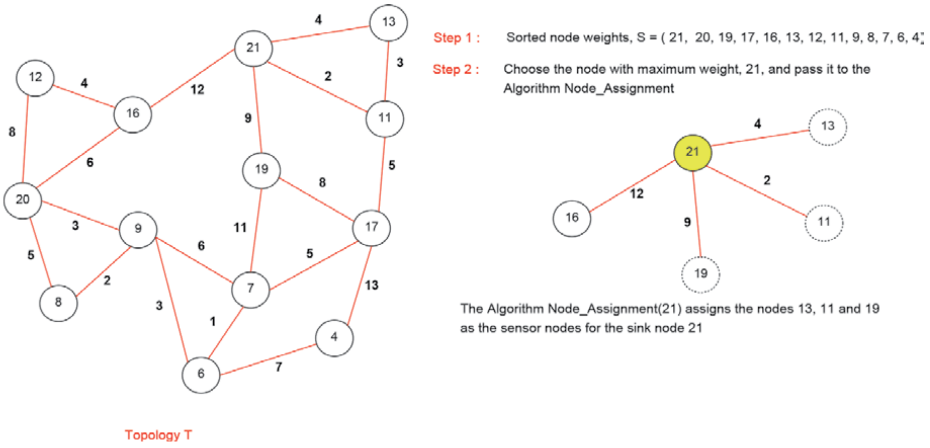
Step 4 : Choose the first unmarked node in S, 17, and pass it to the Algorithm Node_Assignment along with its incident edges

The Algorithm Node_Assignment(17) assigns the node 7 as the sensor node for the sink node 17

Step 5 : Choose the first unmarked node in S, 12, which is an isolated node. Hence, choose the node 12.

Step 6 : Choose the first unmarked node in S, 6. The only incident edge is of weight 7, which which can never be covered by the node 6. So, choose the node 6. The remaining topology has only isolated nodes 4 and 5. Hence, choose both the nodes

Figure 2.
The topology T'' after placing sink node with node weight 20.



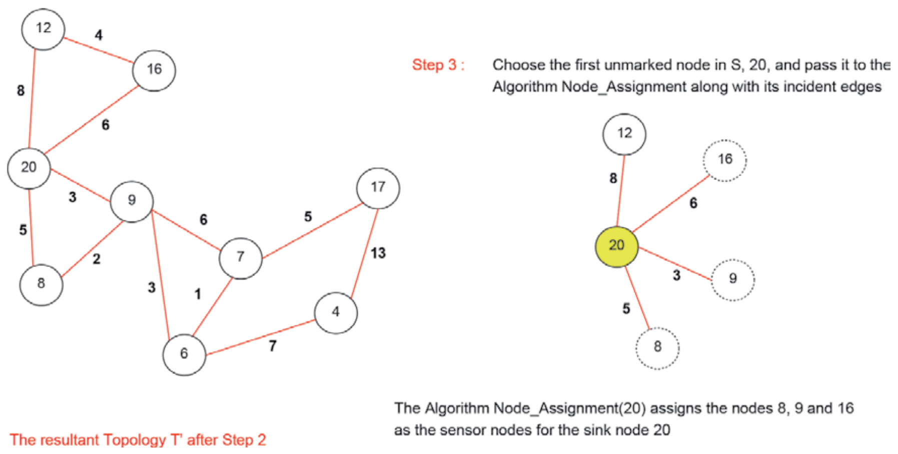
Topology T

Step 1 : Sorted node weights, S = (21, 20, 19, 17, 16, 13, 12, 11, 9, 8, 7, 6, 4

Step 2 : Choose the node with maximum weight, 21, and pass it to the Algorithm Node_Assignment

The Algorithm Node_Assignment(21) assigns the nodes 13, 11 and 19 as the sensor nodes for the sink node 21

Figure 3.
Given topology T with weights.



Step 3 : Choose the first unmarked node in S, 20, and pass it to the Algorithm Node_Assignment along with its incident edges

The Algorithm Node_Assignment(20) assigns the nodes 8, 9 and 16 as the sensor nodes for the sink node 20

The resultant Topology T' after Step 2

Figure 4.
The topology T' after placing sink node with node weight 21.

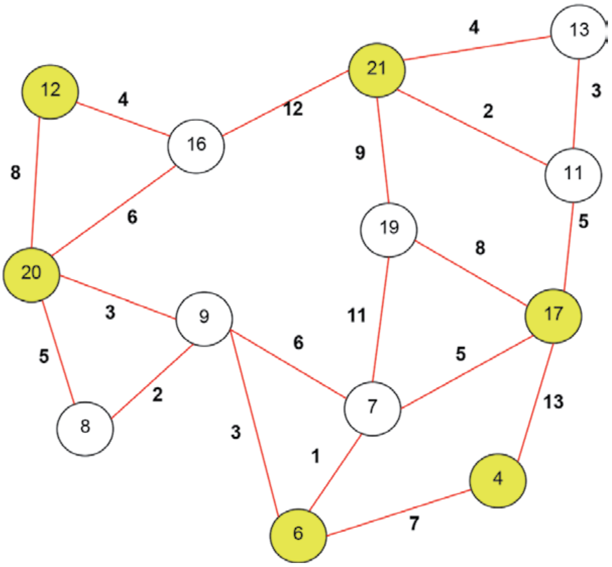


Figure 5.
Final topology after placing all the sink nodes.

the result after 20 is chosen as a sink node and the final topology is shown in **Figure 5**.The node spotted in the final topology represents the position of the sink nodes in topology *T*.

5. Theoretical analysis of proposed approach

For any given output sink node, the maximum capacity is satisfied according the constraint (max. capacity) defined and also all the nodes in the given topology is covered completely.

Theorem 1.1 The solution to the Algorithm 2 is feasible.

Proof: The algorithm is proceeds by marking a node as sink node and also label all the nodes covered by the marked sink node. If unmarked nodes are found, then the algorithm is terminated. Henceforth, in a given topology all nodes are covered completely. Furthermore, the proposed solution 1, does not allow the node capacity beyond its maximum defined capacity. Hence, it is proved that the proposed algorithm is feasible.

The proposed approach uses greedy strategy and gives the approximate solution. For a given instance of proposed approach *Node_Assignment()*, it always provides the optimal solution.

Theorem 1.2 The solution to the Algorithm 1 is optimum.

Proof: Let $x_1, x_2, \dots, x_s$ be the set of nodes of the sorted weights $w_1, w_2, \dots, w_s$ in the given topology T and let the maximum capacity be W. Thus, $w_1 \le w_2 \le \dots \le w_s$.

Let $A = (a_1, \dots, a_s)$ be the output of the algorithm and $B = (b_1, \dots, b_s)$ be any feasible solution, $a_i, b_i \in \{0, 1\}$, $1 \le i \le s$. Note that, $a_i = 1$ (as well as $b_i = 1$) denotes the presence of w_i in the solution and $a_i = 0$ (as well as $b_i = 0$) denotes the absence of w_i in the solution.

Claim 1: If B is *OPTIMUM*, then $\sum b_i \ge \sum a_i$.

The algorithm outputs a feasible solution since the number of $1's$ in *OPTIMUM* $\ge$ number of $1's$ in any feasible solution. Thus the above claim is true.

Observation 1: There exists a $k \in \{1, \dots, n\}$ such that $a_i = 1, 1 \le i \le k - 1$ and $a_j = 0, k \le j \le n$.

Thus, to show that the algorithm is *OPTIMUM*, it is required to establish $\sum a_i \ge \sum b_i$. Towards this end, it is proved that the following sub claim.

Claim 2: If B is any feasible solution, then $\sum a_i \ge \sum b_i$.

Proof for claim 2 is by mathematical induction on m bits, where m is the number of bits in which A and B differ.

Base Case: $m = 0$. Clearly, $\sum a_i \ge \sum b_i$.

Induction Hypothesis: Consider, the claim is true if they differ in less than m-places, $m \ge 0$.

Induction Step: Let A and B differ in $(m + 1)$-places, $m \ge 0$.

Observation 2: Since, A and B differ in $(m + 1)$-places there exists $j, 1 \le j \le k - 1$ such that $a_j = 1$ and $b_j = 0$.

Find the least $j \in \{1, \dots, k - 1\}$ such that $a_j = 1$ and $b_j = 0$. Clearly, it can not be the case that $j \in \{k, \dots, n\}$. If so, then B is not a feasible solution.

Now, set $b_j = 1$ (For example, if $A = (1, 1, 1, 1, 0, 0, \dots, 0)$ and.

$B = (1, 1, 0, 0, 0, 1, \dots, 0)$, then the modified B is $C = (1, 1, 1, 0, 0, 1, \dots, 0)$). By doing this, it is concluded that either the modified B, say C, is feasible or C is not feasible.

Case 1: C is feasible.

Number of positions in which A and C differs is m. By hypothesis, $\sum a_i \ge \sum c_i$. Note that, $\sum c_i \ge \sum b_i$. Thus, $\sum a_i \ge \sum b_i$. Hence, the sub claim is true if C is feasible.

Case 2: C is not feasible.

Since C is not feasible, there exists a $j \in \{k, \dots, n\}$ such that $a_j = 0$ and $c_j = 1$. Now, set $c_j = 0$. This implies, A and the modified C, say D, differs at $(m - 1)$-places and by the induction hypothesis, $\sum a_i \ge \sum d_i$. Observe that $\sum d_i = \sum b_i$. Thus, $\sum a_i \ge \sum b_i$.

From the above said claims, it is concluded that $\sum a_i = \sum b_i$. Hence, the Algorithm 1 provides an optimal solution.

Theorem 1.3 The Algorithm 2 runs in $O(n \log n) + O(n\Delta \log(\Delta))$, where n is the number of nodes in the topology T.

Proof. According to the degree of nodes, the nodes are arranged in decreasing order and it takes $O(n \log n)$ as the worst case complexity. The first maximum degree node is passed as input to the Algorithm 1. The same way the algorithm proceeds with the next maximum degree which is not marked and so on which takes the complexity of $O(\Delta \log (\Delta))$. The Algorithm 1 follows by taking local minimum value and adds to the global sum which satisfies the constraints. The algorithm terminates when it breaks the constraints. Thus, the algorithm produce an optimal solution. So the proposed solution takes the complexity of $O(n \log n) + O(n\Delta \log (\Delta))$ for identifying and assigning the sink node.

6. Results and discussion

The simulation is done with test data taken from the Internet Topology Zoo Archive [13]. There are 261 topologies are available in the data set which indicates a large diversity of network structure. These data sets are gathered from different vendors of networking services. We have made a self written python script to convert Graphical Mark-up Language into adjacency list. The data set contains edge and node informations for the given topology. For a given network, capacity is considered as node value and load is considered as edge weight values. Based on the proposed method, the sink is selected in such a way that the summation of edge weight loads fewer than the total capacity of sink node. The simulation of proposed approach gives us total number of sink nodes required for given topology as shown in the **Table 1**. It is observed that the average number of sink nodes required to manage the given topology is $5-6$.

Name of the Dataset	Number sink nodes
Abilene	4
BelNet	5
UniNett	6
AtmNet	7
Sprint	3
Bell Canada	4
Garr	3
ArpaNet1990	3
Airtel	7

Table 1.
Number of sink nodes vs topology.

7. Conclusion and future work

This chapter proposes an efficient algorithm to place the sink node for the given topological network. This algorithm reduces cost by reducing the number of the sink node being used in the network. Moreover, the placed sink node can serve a maximum number of sensor nodes. The future work is to enhance this approach when a sink node fails in the given topology.

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Chapter 5

Data Aggregation Scheme Using Multiple Mobile Agents in Wireless Sensor Network

Mohamed Younis Mohamed Alzarroug and Wilson Jeberson

Abstract

Wireless sensor networks (WSNs) consist of large number of sensor nodes densely deployed in monitoring area with sensing, wireless communications and computing capabilities. In recent times, wireless sensor networks have used the concept of mobile agent for reducing energy consumption and for effective data collection. The fundamental functionality of WSN is to collect and return data from the sensor nodes. Data aggregation's main goal is to gather and aggregate data in an efficient manner. In data gathering, finding the optimal itinerary planning for the mobile agent is an important step. However, a single mobile agent itinerary planning approach suffers from two drawbacks, task delay and large size of the mobile agent as the scale of the network is expanded. To overcome these drawbacks, this research work proposes: (i) an efficient data aggregation scheme in wireless sensor network that uses multiple mobile agents for aggregating data and transferring it to the sink based on itinerary planning and (ii) an attack detection using TS fuzzy model on multi-mobile agent-based data aggregation scheme is shortly named as MDTSF model.

Keywords: wireless sensor network, data aggregation, TS fuzzy, genetic algorithm and itinerary planning, firefly algorithm, minimum spanning tree (MST)

1. Introduction

Data aggregation signifies inspiring and well-researched topics in the wireless sensor network (WSN) [1–5] writings. The energy restrictions of nodes in a sensor network call for fuel-saving data aggregation approaches and encompass the nexus lifecycle. In addition, mobile agents (MAs) [3, 6] are projected to better the execution of data assemblage in WSNs. In these methodologies, schedules ensuing that traveling agents mainly control the total accomplishment of the collection of the data management. Gathering data effectively has always been of primary importance in a wireless sensor network. The mobile agent paradigm [7, 8] has made it possible to collect and aggregate data in a manner that is proper for real-time applications. Along this line, a number of heuristics have been scheduled to achieve effective itinerary planning for MAs [9].

2. Overview

Inside the complexity of the sensor, sensor nodes perhaps induce dispensable data; similar packets from various junctions can be accumulated to such an extent that the several broadcasts could be condensed. Data aggregation [1] is the mixture of statistics from different origins by using utilities for example repression (eliminating copies), lowest level, highest level, and median. A few of these tasks can be achieved by the aggregator sensor node, by allowing sensory points to supervise data network depletion. Knowing that calculation would be less power absorbing than transmission, considerable reduction in energy can be achieved by data aggregation [10]. The potency of data aggregation can be deduced using many metrics [11].

3. Materials and methods

In recent times the concept of mobile agent (MA) was applied by researchers in wireless sensor networks (WSN) to reduce the energy consumption and improve data collection. Mobile agent paradigm has been adopted by researchers as an alternative to traditional client-server paradigm. Data aggregation in WSN is an active research area due to its importance in solving the main drawbacks of using WSNs. This research has the following contributions.

i. An efficient data aggregation scheme by means of itinerary planning (DAS-IP) using ACO-GA was proposed using the concept of single mobile agent for data aggregation and transfer to sink.

ii. A multi-mobile agent-based data aggregation scheme was proposed to overcome the desk delay problem encountered by single mobile agent itinerary approach.

4. Results and discussion

This section of the chapter offers a comprehensive and concise comparison of the implementation results of the proposed data aggregation schemes with existing ones in terms of the metrics say, delay, energy, drop rate throughput and finally overhead. The performance of the proposed data aggregation schemes are evaluated by contrasting with existing techniques [12, 13].

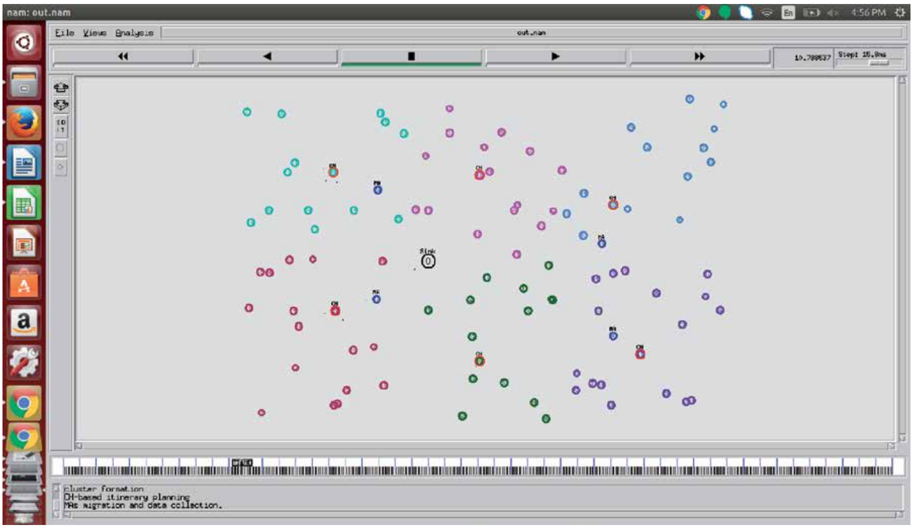
4.1 Performance evaluation of data aggregation scheme using hybrid based ACO-GA itinerary planning

The performance of the proposed data aggregation scheme using hybrid ACO-GA itinerary planning is contrasted with the prevailing techniques say, dynamic based data aggregation approach (DMA-DA). The comparison is done concerning the metrics say, energy, drop rate, throughput and overhead. The experimented was executed on NS-2. **Figure 1** shows the simulated WSN portraying the clusters along with their member nodes together with mobile agents and sink nodes.

The simulation parameters utilized for the experiment are offered in **Table 1**.

4.1.1 Results and comparative analysis of the data aggregation scheme using hybrid based ACO-GA itinerary planning

The performance analysis of the proposed method and prevailing DMA-DA results for the disparate metrics comparison is offered in **Tables 2** and **3** for the number of nodes 100, 200, 300, 400 and 500.



```
cluster formation
CH-based itinerary planning
MAs migration and data collection.
```

Figure 1.
Simulated WSN.

Parameters	Values
No. of nodes	20, 40, 60, 80, 100
Topology area	1000 m × 1000 m
Routing protocol	AODV
MAC type	MAC/802_11
Propagation	Two ray ground
Antenna	Omni antenna
Simulation time	50 seconds
Traffic type	CBR
Packet size	512 bytes
Rate	100 kbps
Channel bandwidth	2.0e6
Initial sending power	0.660
Initial receiving power	0.395
Initial idle power	0.035
Initial energy (Joules)	10.3 J
Channel frequency (Hz)	freq_ 2.4e9
Transmitter signal power (Watt)	Pt_ 0.28
Mobility speed	2–20 m/s

Table 1.
Simulation parameters.

4.1.1.1 Discussion

In **Figure 2** the propounded data aggregation scheme is contrasted to existing DMA-DA concerning the metrics say, delay, delivery ratio and drop rate for different number of nodes. From the above table the proposed method has a delay value

Metrics	Delay		Delivery ratio		Drop	
Number of nodes	**Proposed**	**Existing DMA-DA**	**Proposed**	**Existing DMA-DA**	**Proposed**	**Existing DMA-DA**
100	7.38156	15.308102	0.709117	0.386867	6	25
200	11.28197	17.303762	0.615861	0.272461	9	17
300	15.00316	17.269328	0.382883	0.172134	24	26
400	20.277569	22.16062	0.186749	0.078482	40	378
500	20.409008	25.571875	0.141381	0.058461	158	1034

Table 2.
Juxtaposition of the suggested DAS-IP and the subsisting DMA-DA in terms of metrics such as delay, delivery ratio and drop.

Metrics	Energy		Overhead		Throughput	
Number of nodes	**Proposed**	**Existing DMA-DA**	**Proposed**	**Existing DMA-DA**	**Proposed**	**Existing DMA-DA**
100	6.463972	13.61866	1909	2665	13,542	1031
200	7.80906	13.192729	1857	4775	11,439	1301
300	6.805129	12.490482	2828	6524	10,831	1123
400	6.309804	11.40279	5426	9620	10,133	755
500	5.750889	10.741787	6685	13,291	9452	777

Table 3.
Comparison of the proposed DAS-IP and the existing DMA-DA in terms of metrics such as energy, overhead and throughput.

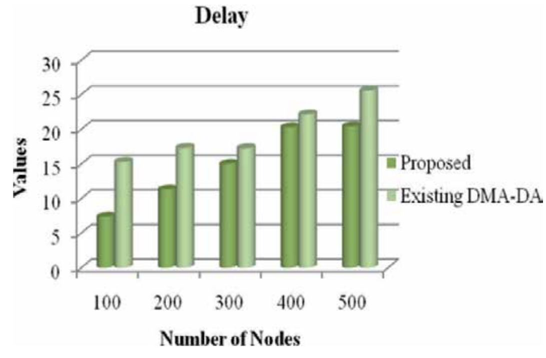


Figure 2.
Performance analysis of the proposed DAS-IP and the existing DMA-DA in terms of delay.

of 7.38156, 11.28197, 15.00316, 20.277569 and 20.277569 while existing DMA-DA data aggregation scheme offers delay values of 15.308102, 17.303762, 17.269328, 22.16062 and 25.571875 for 100, 200, 300, 400 and 500 nodes respectively. The proposed data aggregation scheme based on hybrid ACO-GA itinerary planning offers a delivery ratio of 0.709117, 0.615861, 0.382883, 0.186749 and 0.141381 whereas existing DMA-DA scheme offers 0.386867, 0.272461, 0.172134, 0.078482 and 0.058461 respectively. In terms of the drop values, the proposed scheme offers a value of 6, 9, 24, 40 and 158 while existing DMA-DA has drop values of 25, 17, 26, 378 and 1034 for 100, 200, 300, 400 and 500 nodes respectively.

4.1.1.2 Discussion

Table 3 above displays the experimental outcome of the suggested DAS-IP along with existing DMA-DA technique for 100, 200, 300, 400 and 500 nodes respectively. From the table it can be seen that for a simulation of 100 nodes the proposed DAS-IP offered energy of 6.463972 but the existing DMA-DA has 13.61866, for 200 nodes the energy is 7.80906 and 13.192729 for proposed DAS-IP and prevailing DMA-DA respectively. Similarly the energy for the proposed is 6.805129, 6.309804 and 5.750889 for 300, 400 and 500 nodes respectively while existing DMA-DA offers 12.490482, 11.40279 and 10.741787 for same number of nodes. The proposed data aggregation scheme based on hybrid ACO-GA itinerary planning offers an overhead of 1909, 1857, 2828, 5426 and 6685 whereas existing DMA-DA scheme offers 2665, 4775, 6524, 9620 and 13,291 for 100, 200, 300, 400 and 500 nodes respectively. In terms of throughput values, the proposed scheme offers a value of 13,542, 11,439, 10,831, 10,133 and 9452 while existing DMA-DA has throughput values of 1031, 1301, 1123, 755 and 777 for 100, 200, 300, 400 and 500 nodes respectively.

4.1.2 Delay for the data aggregation scheme using hybrid based ACO-GA itinerary planning

The delay of the proposed data aggregation scheme is contrasted with existing DMA-DA technique for 100, 200, 300, 400 and 500 nodes as illustrated in **Figure 2**. The vertical axis gives the delay value whereas the horizontal axis signifies the number of nodes. The bars in the graph represent the comparisons among the various techniques.

4.1.2.1 Discussion

Figure 2 compares the delay against the number of nodes for the existing DMA-DA and the proposed DAS-IP method. The delay for 100 nodes is 7.38156 and 15.308102 for proposed DAS-IP and existing DMA-IP respectively. For 200 and 300 nodes the delay varies by 6.021792 and 2.266168 values lesser than the prevailing DMA-DA technique. It can be inferred from the figure that the routing delay increases as the number of nodes increases. On considering 500 numbers of nodes, the delay is too high for the existing technique. But, the delay of the proposed technique varies by 5.162867 values lower than the existing one. Also, for any number of nodes when contrasted to the existing one, the proposed DAS-IP shows less delay for the routing data to the sink.

4.1.3 Delivery ratio for the data aggregation scheme using hybrid based ACO-GA itinerary planning (DAS-IP)

The data delivery ratio is given as the total number of data received at destinations (Sink) divided by the total number of data sent from the source node. **Figure 2** offers a comparison among the proposed and existing methods by varying the number of nodes from 100 to 500. In **Figure 3** the vertical axis shows the delivery ratio whereas the horizontal axis denotes the number of nodes used for running the experiments.

4.1.3.1 Discussion

Figure 3 compares the delivery ratio against the number of nodes for the existing DMA-DA and the proposed DAS-IP technique. It can be inferred that the delivery

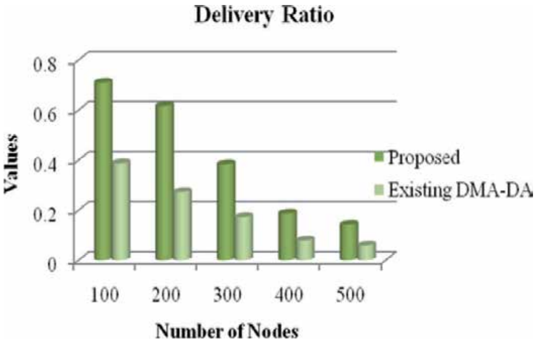


Figure 3.
Performance analysis of the proposed DAS-IP and the existing DMA-DA in terms of delivery ratio.

ratio decreases as the number of nodes increases. For lower number of nodes, say 100, the delivery ratio is too high for the proposed DAS-IP technique and its value is 0.709117, but the delivery ratio is too low for the existing one. For 200 nodes proposed DAS-IP offers a delivery ratio of 0.615861 as against 0.272461 for existing DMA-DA technique, similarly when the node increases 300 the delivery ratio is 0.382883 and 0.172134 for proposed DAS-IP and existing DMA-IP respectively. For higher number of nodes, say 500, the delivery ratio decreases when contrasted to the lower number of nodes. But, in terms of delivery ratio, the proposed technique shows improved results. It is obvious from the graph that the proposed technique exhibits superior performance in terms of delivery ratio.

4.1.4 Drop rate value for the data aggregation scheme using hybrid based ACO-GA itinerary planning (DAS-IP)

The drop value comparison is done on varying number of nodes from 100 to 500 as shown on the graph in **Figure 4.** The vertical axis specifies the drop values and the horizontal axis shows the number of nodes in running the experiment.

4.1.4.1 Discussion

Figure 4 demonstrates the comparison among the drop by varying the number of nodes for the existing DMA-DA and the proposed DAS-IP technique. Experimental outcomes confirm that the drop value rises for higher number of nodes. For 100, 200 and 300 numbers of nodes, the drop value remains constant

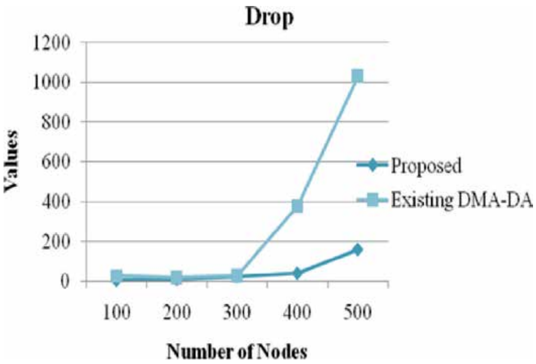


Figure 4.
Performance analysis of the proposed DAS-IP and the existing DMA-DA in terms of drop.

for both the proposed DAS-IP and the existing DMA-DA techniques and increases for 400 and 500 nodes. The existing DMA-DA technique displays the worst performance with drop value of 1034 for 500 nodes. But the proposed technique has the least drop value when contrasted to the existing one. This confirms the predominance of the proposed technique over existing ones.

4.1.5 Energy consumption for the data aggregation scheme using hybrid based ACO-GA itinerary planning (DAS-IP)

EC in the proposed data aggregation technique is contrasted with existing DMA-DA technique. The EC is given in the graph as illustrated in **Figure 5**. The vertical axis signifies the EC values in Kilowatts-hour (KWH) whereas the horizontal axis shows the number of nodes in running the experiments.

4.1.5.1 Discussion

Figure 5 compares the EC against the number of nodes for the prevailing DMA-DA and the proposed DAS-IP technique. For 100 and 200 nodes the EC for the proposed DAS-IP are 6.463972 and 7.80906 while prevailing DMA-DA offers relatively high EC of 13.61866 and 13.192729 KWH respectively. Interestingly for 300, 400 and 500 nodes the EC drops to 6.805129, 6.309804 and 5.750889 for the proposed technique. The compared existing technique consumes huge amount of energy for any number of nodes. The same is the case for existing DMA-DA. Therefore the proposed technique has the superior performance in comparison to existing DMA-DA.

4.1.6 Overhead for the data aggregation scheme using hybrid based ACO-GA itinerary planning (DAS-IP)

The Overhead value of the proposed DAS-IP technique is contrasted with existing DMA-DA. The overhead comparison appears in **Figure 6**. The vertical axis displays the overhead values while the horizontal axis shows the number of nodes in executing the experiment.

4.1.6.1 Discussion

Figure 6 compares the overhead against the number of nodes for the existing DMA-DA and the proposed DAS-IP technique. For 100, 200, 300, 400 and

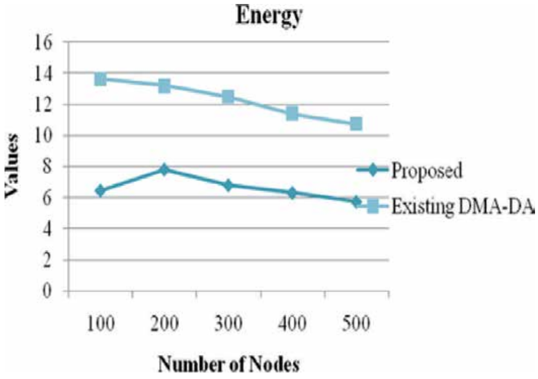


Figure 5.
Performance analysis of the proposed DAS-IP and the existing DMA-DA in terms of energy.

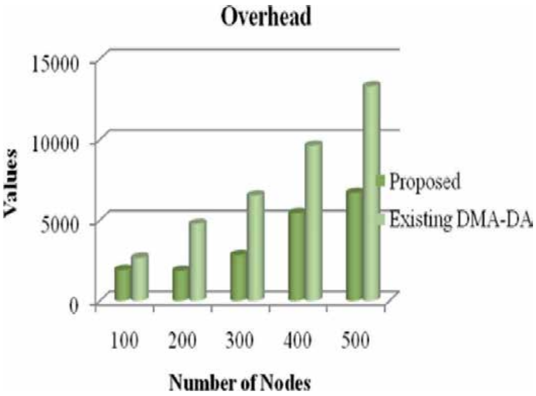


Figure 6.
Performance analysis of the proposed DAS-IP and the existing DMA-DA in terms of overhead.

500 nodes the overhead for proposed DAS-IP are 1909, 1857, 2828, 5426 and 6685 respectively while the prevailing DMA-DA offers 2665, 4775, 6524, 9620, 13,291 for same number of nodes. It is evident from the graph that, as the number of nodes increases, the overhead for the proposed and the existing also increases. The proposed technique has the least overhead in all the cases. Therefore, the proposed demonstrates superior performance on the basis of overhead as compared to existing DMA-DA.

4.1.7 Throughput for the data aggregation scheme using hybrid based ACO-GA itinerary planning (DAS-IP)

The comparison of throughput for the proposed DAS-IP and prevailing DMA-DA appears in **Figure 7**. The horizontal axis signifies the throughput in kbps while vertical axis signify the number of nodes in running the experiment.

4.1.7.1 Discussion

Figure 7 offers comparison of the output over the number of nodes for the prevailing DMA-DA and the contemplated DAS-IP process. Production is the amount of data groups triumphantly shifted from a starting point to a finish in a given time. For 100 nodes, the outturn is13542 which is more for the recommended form and it lessens as the node escalates. For 200, 300, 400 and 500 nodes the proposed DAS-IP technique has a throughput of 11,439, 10,831, 10,133 and 9452 which is higher as compared to prevailing DMA-DA which offers 1301, 1123, 755 and 777 for 200,

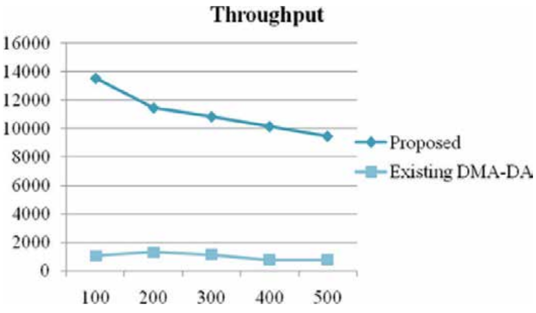


Figure 7.
Examination of presentation of the projected DAS-IP and the actual DMA-DA in means of throughput.

300, 400 and 500 nodes respectively. This proves the superiority of the proposed technique on contrasted to prevailing DMA-DA.

4.1.8 Performance evaluation of multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The performance of the proposed multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF) is contrasted with the prevailing techniques say, LEACH and T-LEACH techniques. The comparison is done concerning the metrics say, energy consumption, end to end delay, packet drop rate, and throughput and network life time.

4.1.9 Results and comparative analysis of multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The performance analysis of the proposed MDTSF model and existing LEACH and T-LEACH results for the disparate metrics comparison is offered in **Table 4** for the number of attacks 1, 2, 3, 4 and 5.

4.1.9.1 Discussion

Table 4 above displays the experimental result of the proposed MDTSF technique along with the existing LEACH and T-LEACH mechanisms for 1 to 5 attacks. The proposed MDTSF model uses energy of 6.25345, 5.8712, 4.9484, 5.2896 and 5.1357 for 1, 2, 3, 4 and 5 attacks respectively while existing LEACH uses 9.2384, 10.4587, 9.5647, 10.9874 and 11.2689 respectively. Similarly the energy consumption for existing T-LEACH is 11.2856, 12.8516, 10.2587, 9.2587 and 10.2658 for 1, 2, 3, 4 and 5 attacks respectively. In terms of end to end delay the proposed MDTSF, existing LEACH and T-LEACH offers 5.1458, 0.7548 and 0.6325 for 1 attack. It then rises to 12.2368, 0.4585 and 0.3547 when the attack increases to 5 for proposed MDTSF, existing LEACH and T-LEACH respectively.

4.1.10 End to end delay for multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The end to end delay of the proposed MDTSF model is contrasted with existing LEACH and T-LEACH models for 1, 2, 3, 4 and 5 attacks as illustrated in **Figure 8.** The vertical axis gives the delay value (in seconds) whereas the horizontal axis signifies the number of attacks. The bars in the graph represent the comparisons among the various techniques.

No of attacks	Energy consumption (EC)			End to end delay		
	Proposed	LEACH	T-LEACH	Proposed	LEACH	T-LEACH
1	6.2534	9.2384	11.2856	5.1458	0.7548	0.6325
2	5.8712	10.4587	12.8516	7.5648	0.7122	0.5912
3	4.9484	9.5647	10.2587	8.1234	0.6145	0.5312
4	5.2896	10.9874	9.2587	10.2635	0.5587	0.3851
5	5.1357	11.2689	10.2658	12.2368	0.4585	0.3547

Table 4.
Performance analysis of proposed and existing techniques in terms of EC and end to end delay.

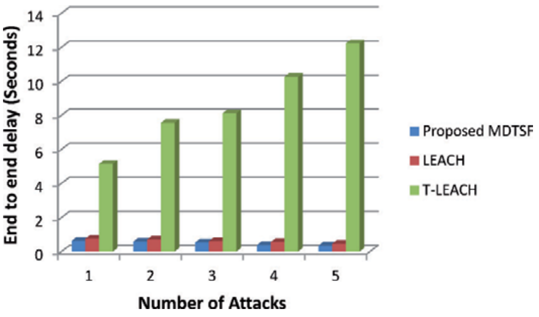


Figure 8.
End to end delay analysis of the proposed MDTSF with the existing methods.

4.1.10.1 Discussion

Figure 8 shows the end to end delay comparison of the proposed MDTSF model against existing LEACH and T-LEACH. The proposed MDTSF model offers a delay of 0.6325, 0.5912, 0.5312, 0.3851 and 0.3547 for 1, 2, 3, 4 and 5 attacks respectively whereas existing T-LEACH produces the highest delay of 5.1458, 7.5648, 8.1234, 10.2635 and 12.2368 for same number of attacks. The delay ratio increases marginally as the number of attacks increases. But the proposed method's delay is lower than existent methods for very attacks. The proposed work has a lower network delay contrasted with other existent methods.

4.1.11 Energy consumption for multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

EC in the proposed MDTSF technique is contrasted with existing LEACH and T-LEACH technique. The EC is given in the graph as illustrated in **Figure 9**. The vertical axis signifies the EC values in Kilowatts-hour (KWH) whereas the horizontal axis shows the number of attacks in running the experiments.

4.1.11.1 Discussion

Figure 9 shows the EC comparison graph of the proposed MDTSF model with the existing LEACH and T-LEACH. The proposed MDTSF model uses energy of 6.25345, 5.8712, 4.9484, 5.2896 and 5.1357 for 1, 2, 3, 4 and 5 attacks respectively

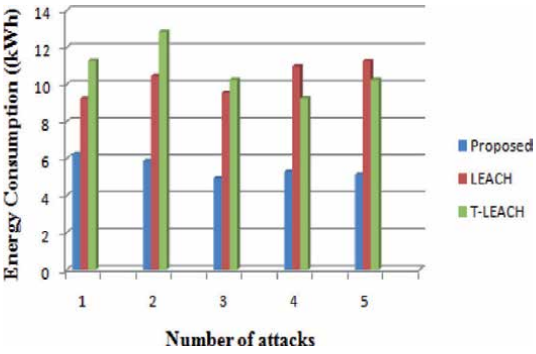


Figure 9.
Performance comparison of proposed and existing methods in terms of EC.

while existing LEACH uses 9.2384, 10.4587, 9.5647, 10.9874 and 11.2689 respectively. Similarly the energy consumption for existing T-LEACH is 11.2856, 12.8516, 10.2587, 9.2587 and 10.2658 for 1, 2, 3, 4 and 5 attacks respectively. The above graph signifies that the proposed model attained the lowest energy consumption. For the number of attacks, EC has increases and decreases gradually, but it is very low while compared to the existing LEACH and T-LEACH. For better communication, the value of EC should be low to prevent the node from network failure. The proposed method achieves this lower energy consumption for every attack.

4.1.12 Packet drop rate for multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The packet drop rate (PDR) comparison of the proposed MDTSF and existing LEACH and T-LEACH is done by the varying number of attacks from 1 to 5 as shown on the graph in **Figure 10.** The vertical axis specifies the packet drop rate values and the horizontal axis shows the number of attacks in running the experiment.

4.1.12.1 Discussion

Figure 10 portrays the PDR by varying the number of attacks from 1 to 5. It is evident from the graph that the PDR has decreased in the proposed MDTSF model when contrasted to the existing methods. For optimal transmission of network, the PDR should be low. For first attack, the PDR of existing LEACH and T-LEACH are 0.8 and 1.12%, but the proposed method has 0.25% of packet drop rate. The graph confirms that the proposed method has the least PDR value than existing techniques for remaining four attacks. PDR of proposed method slowly increase son contrasting to other existing techniques. The least PDR of the proposed technique confirms its predominance over existing ones.

4.1.13 Throughput for multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The comparison of throughput for the proposed MDTSF and prevailing LEACH and T-LEACH appears in **Figure 11**. The horizontal axis signifies the throughput in kbps while vertical axis signifies the number of attacks in running the experiment.

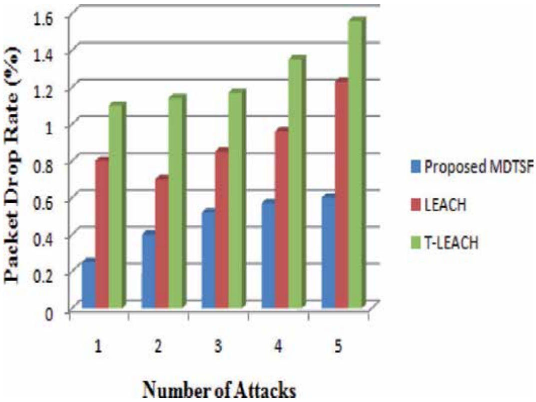


Figure 10.
Packet drop of proposed and existing techniques.

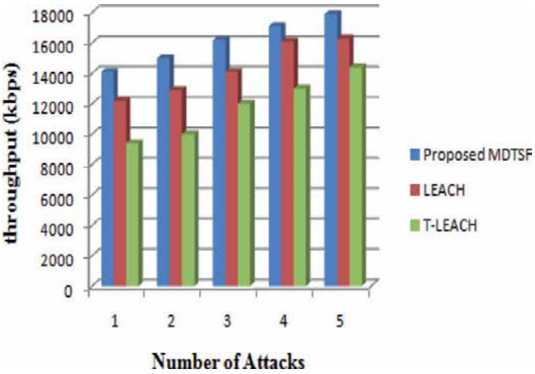


Figure 11.
Throughput analysis of proposed and existing technique.

4.1.13.1 Discussion

Figure 11 shows the throughput analysis of the proposed MDTSF and existing LEACH and T-LEACH methods. The graph clearly reveals that the proposed MDTSF has achieved the best throughput in comparison to other existent techniques. For the first attack, proposed MDTSF achieved 14,523 throughput values, while the existing LEACH and T-LEACH attains throughput values of 12,564 and 9568 for first attack. The proposed MDTSF has the highest throughput in all cases. Analysis of the techniques confirms the superiority of the proposed MDTSF model over existing ones.

4.1.14 Network life time of the multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

The network life time of the proposed MDTSF technique is contrasted with existing LEACH and T-LEACH. The life time comparison appears in **Figure 12**. The vertical axis displays the network life time values in hours while the horizontal axis shows the number of attacks in executing the experiment. The proposed and existing methods lifetime is compared as shown in **Figure 12**.

4.1.14.1 Discussion

Figure 12 shows the comparison of the proposed MDTSF and existing LEACH and T-LEACH in terms of network lifetime. Network lifetime should be high for achieving an optimum network performance. In this case, performance of the network is evaluated based on the number attack occurring in the course of data aggregation in the network and lifetime of the network diminishes linearly when number of attacks are increase as shown in the graph. But the lifetime of the proposed technique is higher than existing methods. Hence it is proved that the MDTSF has highest lifetime.

4.1.15 Packet delivery ratio of the multi-mobile agent-based data aggregation scheme using TS fuzzy model (MDTSF)

Figure 13 offers a comparison among the proposed and existing methods by varying the number of attacks from 1 through 5. In **Figure 13** the vertical axis shows the packet delivery ratio whereas the horizontal axis denotes the number of attacks used for running the experiments.

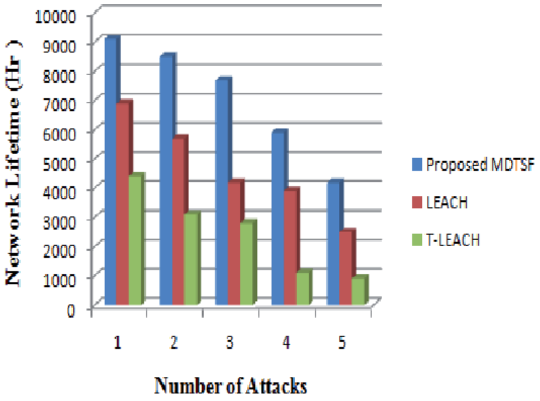


Figure 12.
Comparison graph of network lifetime for proposed and existing systems.

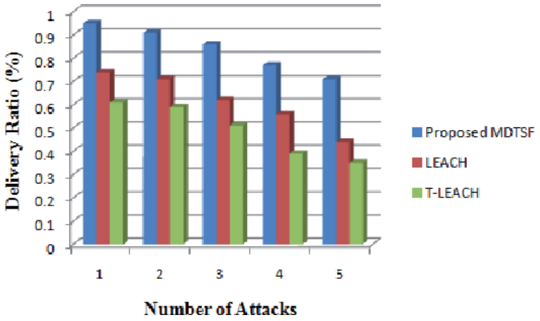


Figure 13.
Performance comparison of the proposed MDTSF with existing LEACH and T-LEACH.

4.1.15.1 Discussion

Figure 13 compares the packet delivery ratio performance of the proposed and existing techniques. For efficient data transmission in the network, packet delivery ratio should be high. If the packet delivery ratio has a highest value then, all the information are obtained at the receiver side without any data loss. From **Figure 13**, the graph clearly shows that the proposed MDTSF achieves the best value of 0.9485% but the existing techniques achieve less delivery ratio. Thus, it can be proves that the proposed MDTSF offers superior performance on compared to other existent methods.

5. Summary

In WSN, the communication cost is mostly greater than computational cost. Data aggregation is an ideal way of optimizing the communication cost. This can be achieved by accumulating the sensor readings. In this given thesis, an efficient data aggregation scheme based on itinerary approach is presented using multiple mobile agents aimed at accumulating and transferring data to the sink. Inside the proposed strategy a hybrid ACO-GA aimed at itinerary planning is engaged, cluster formation was done by aid of FCM algorithm. A progression of experiments is led and the outcome for the proposed data aggregation scheme is compared with existing ones. The experimental outcomes were compared with existing techniques to demonstrate the predominance of the proposed data aggregation schemes over latest methodologies pertaining to the metrics say, end to end delay, delivery ratio, drop rate, energy consumption (EC), overhead and finally throughput.

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Chapter 6

Data Collection Protocols in Wireless Sensor Networks

Koppala Guravaiah, Arumugam Kavitha and Rengaraj Leela Velusamy

Abstract

In recent years, wireless sensor networks have became the effective solutions for a wide range of IoT applications. The major task of this network is data collection, which is the process of sensing the environment, collecting relevant data, and sending them to the server or BS. In this chapter, classification of data collection protocols are presented with the help of different parameters such as network lifetime, energy, fault tolerance, and latency. To achieve these parameters, different techniques such as multi-hop, clustering, duty cycling, network coding, aggregation, sink mobility, directional antennas, and cross-layer solutions have been analyzed. The drawbacks of these techniques are discussed. Finally, the future work for routing protocols in wireless sensor networks is discussed.

Keywords: wireless sensor networks, routing protocols, data collection, network lifetime, energy efficiency, fault tolerance, low latency

1. Introduction

Wireless sensor networks (WSNs) [1] are distributed among environment with lightweight and small sensor nodes. These sensor nodes are used to measure the parameters of environment. Some of such parameters are vibration, pressure, sound, movements, temperature, humidity, etc. The sensors are well coordinated and connected to the base station (BS) or sink using wireless communication for forwarding sensed information. Due to this, many IoT-based applications such as home applications [2], vehicular monitoring [3], medical applications, structural monitoring, habitat monitoring, intrusion detection, tracking for military purpose, etc., are using WSNs for data collection [1, 4, 5].

Ad hoc and cellular network routing protocols are not suitable for sensor networks due to the sensor node design challenges such as node deployment, node mobility, and limited resource constraints (battery, communication, and processing capabilities) [6]. In WSNs, large number of sensor nodes are deployed for specific application due to this global addressing which is too difficult to maintain. Due to this large number, nodes located in the same area may generate redundant data and transmit to BS. This leads to bandwidth wastage and network traffic which in turn effects the more energy consumption. Another main resource constraint of a sensor node is limited battery power due to battery replacement or recharge not being possible in most of the WSN applications. WSN has a wireless communication medium, which

Data collection	Applications		EE	LT	LL	FT	S	Q	R
Regular data collection	Health care	Patient monitoring	M	M	H	H	H	H	H
	Military	Battlefield surveillance	H	H	H	H	H	H	H
		Structural monitoring	H	H	H	H	M	M	H
	Public	Factory monitoring	M	M	H	M	M	M	H
	Industrial	Machine monitoring	M	M	H	M	L	M	H
	Safety	Chemical monitoring	M	M	H	M	M	M	H
	Environmental	Disaster monitoring	H	H	H	H	L	M	M
		Traffic control and monitoring	M	M	H	H	M	H	M
Non-regular data collection	Agriculture	Precision agriculture	H	H	L	M	L	L	H
		Environment control in buildings	M	M	M	L	L	L	M
	Industrial	Managing inventory control	M	M	M	L	L	L	M
	Home	Smart home automation	M	M	L	L	L	L	M
		Animal monitoring	H	H	L	L	L	L	M
	Environmental	Vehicle tracking and detection	H	H	L	L	L	M	M
		Disaster damage assessment	M	M	L	L	L	M	M

EE: energy efficiency; LT: lifetime; LL: low latency; FT: fault tolerance; S: scalability; Q: quality of service; R: reliability; L: low; M: medium; H: high.

Table 1.
WSN applications based on data collection requirements.

leads to an increased probability of collisions in the data communication process and which impacts on the network performance. While designing a new data collection routing protocol and achieving its requirements such as coverage area, data accuracy, and low latency, we need to consider the above stated issues [7].

In WSN, collection of sensed data can be done in a regular or non-regular mode. Data have to be collected continuously from sensor nodes in regular mode. Whereas, in the non-regular mode, the data have to be collected at some periodic intervals from sensor nodes. **Table 1** refers to different design metrics such as energy efficiency (EE), lifetime (LT), low latency (LL), fault tolerance (FT), security (S), quality of service (Q), and reliability (R), which are considered with the level of importance [low (L), medium (M), and high (H)] for different WSN applications.

This chapter's main objective is the better understanding of data collection protocol with respect to network lifetime, energy conservation, fault tolerance, and low latency. In addition to this, understanding of some existing techniques such as multi-hop, clustering, duty cycling, aggregation, directional antennas, network coding, sink mobility, and cross-layer solutions for achieving these parameters.

2. Data collection

For sensing the data from the environment and transferring to the BS, the sensor nodes are deployed at specific locations. The data collection's main goal is accuracy of sensing and transmitting the data to BS without any information loss and delay.

Transmitting of sensed data to BS is either by data dissemination (data diffusion) or data gathering (data delivery) [8]. Data/queries (network setup/management and/or control collection commands) propagation throughout the network is done in the data dissemination stage. Low latency is the main issue for disseminating data/queries to BS.

Data delivery or data gathering is the forwarding of sensed data to the BS. The main aim of data gathering is to maximize the number of rounds of data transferring toward BS before the network died. This will be achieved by minimizing energy consumption and delay for each transmission.

Single-hop or multi-hop is the basic communication technique between source sensor node and BS in data gathering. Sensed data are forwarded directly to BS in the single-hop communication. In multi-hop [9], the sensed data are forwarded to the base station with the help of intermediate sensor nodes. In multi-hop routing, energy conservation, route discovery, QoS, and low latency are the major issues. Introducing mobility in sink nodes, called mobile sinks or mobile collectors [10] is also a single-hop communication. In this network, mobile sink nodes move along a trajectory path to access the data from all source sensor nodes in a single-hop fashion. The trajectory path identification is the important step in this single-hop communication to cover all the nodes throughout the network. Energy conservation and mobility are the major issues in mobility-based single-hop data transmission.

2.1 Taxonomy of data collection protocols

Different classification of data collection routing protocols [6, 11–15] are proposed in recent years by researchers. **Figure 1** shows the different classifications of data collection routing protocols.

Network architecture-based classification was presented by Akkaya et al. [6] in 2005. According to Akkaya et al., routing protocols are classified as data-centric, hierarchical, and location-based protocols. Sink disseminating the queries in network to get the sensor data from sensor nodes is the work of data-centric protocols. In cluster- or hierarchical-based protocols, network of nodes is divided into clusters and each cluster is managed by the cluster head (CH). Each CH will receive the sensed data from the corresponding cluster member and forward it to the BS. Aggregation techniques can be used by the CH to save energy while forwarding to BS. Geographic- or location-based protocols are considering the position information of sensor nodes for routing.

Multipath, query-based, negotiation-based, quality of service (QoS)-based, and coherent-based protocols are the classification of routing protocols as given by Karaki et al. [11]. In multipath routing, multiple paths are selected for achieving a variety of benefits such as reliability, fault tolerance, and increased bandwidth. Data

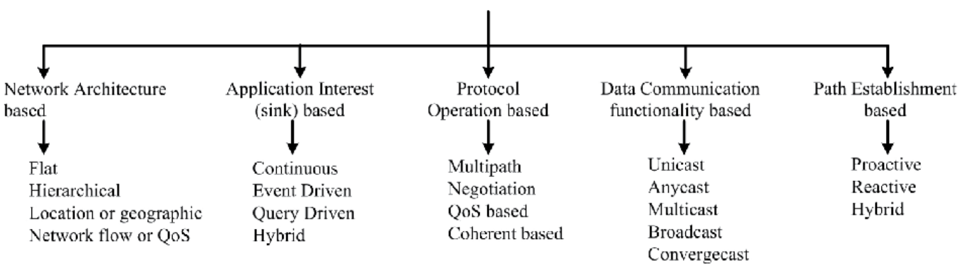

Figure 1.
Taxonomy of data collection protocols.

acquisition is done by the sink node with the help of query dissemination in query-based routing. All sensor nodes are going to store the data based on the interest of nodes. Then the data are forwarded to the destination only if the sensed or received node data match with the received queries. Data descriptors are used by negotiation-based protocols for reducing redundant data relays through negotiation. QoS-based protocols mainly consider QoS metrics such as delay, throughput, bandwidth, etc., when routing the data to the base station. In coherent routing, the sensed data is transferred directly to the aggregate node. Whereas in noncoherent routing, node data processing is done locally and then is transferred to neighbor nodes. In addition, routing protocols are classified into proactive, reactive, and hybrid protocols depending on path establishment between the source and destination.

Continuous, event-driven, observer-initiated, and hybrid-based on application interest are the different classifications given by Tilak et al. [12] in 2002. The sensor nodes transfer their sensed data at a prespecified rate to the server in the continuous model. Only when an event occurs, the sensor nodes forward data to base station in the event-driven data model. In the observer-initiated model, the observer will give an explicit request, then only the corresponding sensor nodes respond with the results. The combination of above three approaches will be called as hybrid protocols.

Based on data communication functionalities of routing protocols, Kai Han et al. [31], in 2013, classified the routing protocols into unicast, anycast, broadcast, multicast, and converge-cast. One-to-one association between sensor nodes is used in unicast routing. For forwarding the sensed data, unicast routing is using one neighboring node as a relay node. In anycast routing, nodes transfer the sensed data to a potential receiver node of a group. Multicast routing is transferring the data to a selected number of neighbor nodes simultaneously in a single transmission. Broadcast routing uses a one-to-many association; in a single transmission, sensor nodes transfer the data to their all neighbor nodes simultaneously. The data are aggregated at relay nodes and forwarded toward the base station in the converge-cast mechanism. Information exchanges will be done between the pair of sensor nodes in unicast/anycast. Whereas, multicast/broadcast is required for disseminating commands to sensor nodes, and converge-cast uses to collect the data from sensor nodes.

Routing protocols are classified as classical and swarm intelligence-based protocols by A.M. Zungeru et al. [14]. Further, each protocol is categorized into data-centric, hierarchical, location-based, network flow, and quality of service (QoS) awareness. In addition, they divided the routing protocols into proactive, reactive, and hybrid, depending on the path establishment between the source and destination.

The energy-efficient routing protocols are classified into network structure, communication model, topology-based, and reliable routing, as presented by Pantazis et al. [15]. Network structure routing protocols are classified into flat and hierarchical protocols. Communication model routing protocols can be divided into coherent or query-based and negotiation-based or noncoherent-based protocols. Mobile agent-based or location-based routing protocols are under the category of topology-based routing protocols. Reliable routing protocols are classified as multipath-based or QoS-based.

In addition to the above, some other literature [16–20] also presented different classifications of routing protocol. However, **Figure 1** represents the overall classification of routing protocols in WSN.

3. Major design issues and techniques for data collection

In this section, some common design issues for data collection, such as energy, lifetime, latency, and fault tolerance are discussed. The techniques such as clustering, aggregation, network coding, duty cycling, directional antennas, sink mobility, and cross-layer solutions which are used to achieve efficient data collection routing protocols are also presented.

3.1 Design issues in data collection

3.1.1 Energy and lifetime

Managing energy of the sensor nodes is the primary concern in WSN because it is the critical constraint of the sensor nodes. Saving of the node energy increases the network lifetime. Sensor node depletes much energy in two significant operations such as environment sensing and communicating sensed data to the BS. Energy consumption is stable for sensing operation because it depends on the sampling rate and does not depend on the other factors such as the topology of network or the location of the sensors. While, data forwarding process depends on them. Hence, energy conservation is feasible by designing an effective data forwarding process. Network lifetime [21] is defined as the period from the starting of the WSN operation to the time when any or a given percentage of sensor nodes die. Hence, the major objective of the data collection protocol is to gather the data with the maximum number of rounds within the lifetime of the network. The data gathering is the vital factor which considers energy saving as well as lifetime. In literature [4, 22], the authors have presented energy-efficient techniques for data collection. Rault et al. [4] have reviewed the energy-saving techniques and its classification such as radio optimization, data reduction, sleep/wake-up schemes, energy-efficient routing, and battery repletion. Anastasi et al. [22] in 2009 discussed directions for energy conservation in WSNs and presented the taxonomy of energy conservation techniques such as duty cycling, data driven, and mobility-based routing.

3.1.2 Latency

Latency is the period from the time unit that the data generation at the sensor node started to the time unit that data reception was completed at the base station. It is one of the main concerns for time significant applications such as military and medical health-care monitoring. Attaining low latency is a vital concern because of the following reasons:

1. Due to limited constraints of sensor nodes which are more prone to failure.

2. Collisions and network traffic will be increased due to the broadcast nature of radio channel.

3. Same kind of data will be sensed by densely deployed sensors and transfer to BS will increase the network traffic and exhaust the communication bandwidth.

To deal with the above issues, there is a need for low-latency protocols. Literature [23, 24] presents recent survey works on low-latency routing protocols. Srivathsan and Iyengar [23] have reviewed some key mechanisms to reduce the latency in single-hop and multi-hop wireless sensor networks; such mechanisms are sampling time, propagation time, processing time, scheduling, use of directional antennas, MAC protocols, sleep/wake-up cycles, predictions, use of dual-frequency radios, etc.

A review on energy-efficient and low-latency routing protocols for WSNs without dominating the other design factors is presented by Bagyalakshmi et al. [24].

3.1.3 Fault tolerance

Fault tolerance [25] enhances the availability, reliability, and dependability of the system by ensuring the usage availability of the system without any disruption in the presence of faults. In WSN, fault tolerance is also a demanding issue due to the sensor nodes more vulnerable to failure because of energy depletions, desynchronization, communication link errors, etc., which are provoked owing to hardware and software failures, environmental conditions, etc. Hence, fault management in WSN must be administered with additional care. Initial review works on fault-tolerant routing schemes are present in literature [21, 25–28]. Yu et al. [26] have explained issues in the fault management of WSN. Three phases called fault diagnosis, fault detection, and fault recovery for supervising faults have been proposed. In fault detection phase, an unexpected failure should be identified by the system. Literature [26–28] explains various fault detection techniques. In fault diagnosis phase, comprehensive description or model has been determined to distinguish various faults in WSNs [21] or fault recovery action. In the fault recovery phase, the sensor network is redesigned from failures or fault nodes to enhance the network performance. Fault recovery techniques have been dealt by literature [25].

3.2 Major techniques used for data collection design issues

The major techniques utilized for attaining energy saving, low latency, long lifetime, and fault tolerance in WSNs are discussed in this section.

3.2.1 Cluster architecture

Cluster-based architecture is a foremost technique for effective energy conservation. In this mechanism, the network is partitioned into clusters, where the cluster head (CH) is a leader to manage the members of each cluster. Every member sensor node transmits the sensed data to their corresponding CH; then, CHs communicate the collected data to the BS. This technique avoids flooding, routing loops, and multiple routes; hence, reduced network traffic and low latency are attained. The major advantage of cluster-based architecture is that it needs less transmission power because of small communication ranges within the cluster. The CH uses the fusion mechanism to minimize the size of the transmission data. CH selection is performed in a rotation basis to balance the energy consumption in the network and improve the network lifetime. However, in cluster-based routing protocols, cluster head selection plays a critical role. Further, clustering algorithms do not consider the location of the base station, which creates a hot spot problem in multi-hop wireless sensor networks.

3.2.2 Data aggregation

Data aggregation is one of the significant methods applied to aggregate the raw data evolved from multiple sources. In data aggregation schemes, nodes receive the data, reduce the amount of data by employing data aggregation techniques, and then transmit the data to the BS. The average or minimum amount of received data are merely forwarded by the received node. This reduces the network traffic and hence low latency is achieved. However, the base station (sink) cannot ensure the accuracy of the aggregated data that have been received by it and also cannot restore the data.

3.2.3 Network coding

Network coding is the same as the aggregation technique. In this technique, the nodes collect the data from neighbor nodes and combine them together by applying mathematical operations; then it transmits data to the BS. This technique improves the network throughput, reliability, energy efficiency, and scalability; it is also resilient to attacks and eavesdropping. Network traffic in broadcast scenarios can be reduced by combining several packets as a single packet rather than sending separate packets.

3.2.4 Duty cycling

For energy conservation, duty cycling is one of the important techniques in WSNs. In duty cycling, the radio transceiver mode of sensor node is changing between active and sleep. This technique requires cooperative coordination between nodes for communication. Nodes want to communicate with each other and the nodes will shift from sleep mode to wake-up mode. A node must wait for its neighbor nodes to awake for communication. Sleep latency is increased due to this. Multi-hop broadcasting is complex in this technique because all the neighboring nodes are not active at the same time.

3.2.5 Directional antennas

Transmitting or receiving signals with one or more directions at a time with greater power is done with directional antennas. This technique improves the performance with respect to throughput by increasing the transmission range. With the help of directional antennas, bandwidth reusability is also possible. However, transmission power calculations and optimal antenna pattern selection overhead is more in these directional antennas. Also, directional antennas are more exposed to hidden and exposed terminal problems.

3.2.6 Sink mobility

Sink mobility is one of the energy-efficient technique, where mobility is introduced with sink nodes. The mobile sink nodes collect the data from sensor nodes with single-hop while moving in a specified path and then forward the same to the BS. This scheme reduces the workload of nodes which are placed nearer to the sink nodes and it increases the network lifetime. With the help of sink mobility, so many sparse networks can be connected and communicated which in turn provides scalability of the network. Reliability will be improved because of single-hop communication between the mobile sink and sensor nodes. However, trajectory path maintenance is a critical part of sink node while moving. Mobile collector needs a proper synchronization mechanism with sensor nodes, otherwise this causes packet loss while data gathering.

3.2.7 Cross-layered approach

When compared to layered approaches, cross-layered approach in WSN is energy efficient. The protocol stack is considered as a single system instead of individual layers in the cross-layered approach. For interaction among the protocol layers, state information of the protocols is shared among all layers. Cross-layered protocol implementations significantly affect the system efficiency with respect to the energy and lifetime.

4. Existing routing techniques

In WSN, so many techniques are proposed to achieve energy efficiency, longer lifetime, fault tolerance. Low latency by different researchers are briefly explained in this section. Most of these solutions are designed based on different techniques such as clustering, network coding, duty cycling, aggregation, directional antennas, sink mobility, and cross-layer solutions.

Low-energy adaptive clustering hierarchy (LEACH) routing strategy was proposed by Heinzelman et al. [29]. It is a cluster-based routing algorithm to decrease energy consumption and improve the network lifetime. In this protocol, the network is divided into clusters; each cluster contains a set of CMs and a leader called CH. The CMs send the data to its respective CH; CHs communicate the collected data to the BS and are elected in a random and distributed manner. Subsequently, LEACH was altered to LEACH-C [30], a centralized approach. The process of CH selection is performed based on the residual energy of the sensor nodes. However, due to dynamic cluster formation, the distance between CH and BS is faraway and some of the cluster nodes are also faraway from the CHs; it increases the communication cost. Later, a lot of modified LEACH protocols have been proposed to enhance the network lifetime and have been reviewed in [17].

LEACH protocol has been improved as power-efficient gathering in information systems (PEGASIS) [31], a multi-hop chain-based protocol, where every node aids in transmitting and/or receiving the data from its neighbor node by forming the chain. The collected data are aggregated and carried from node to node. One of the nodes in the chain is selected as a leader; the leader node transfers data to the BS. PEGASIS performs better than LEACH by minimizing the number of transmissions from sensor nodes to BS and clustering overhead. However, data transmission delay is higher due to the large chain length.

Threshold-sensitive energy-efficient sensor network protocol (TEEN) [32] is a homogenous reactive routing protocol. In this approach, the process of CH selection is performed similar to LEACH; the data transmission varies from LEACH. The workings of TEEN are based on the thresholds, namely, Hard threshold (H_T) and soft threshold (S_T). However, the CH selection process is random and the size of the clusters is unequal; it causes an unbalanced energy consumption among the clusters. Network throughput is also decreased due to the threshold mechanism.

Hybrid energy-efficient distributed (HEED) protocol [33] has been proposed by Younis and Fahmy. It is a homogenous cluster-based routing protocol; CH selection is accomplished based on the probability function of residual energy and node degree. Later, HEED protocol is extended as the heterogeneous HEED to manage the routing in the heterogeneous network field. This protocol utilizes fuzzy logic model for the CH selection process; the parameters considered in the fuzzy logic model are node degree, distance, and remaining energy. Finally, direct data transmission is carried out between the CM and CH and between the CH and BS.

Qing et al. [34] have presented distributed energy-efficient clustering scheme (DEEC), a heterogeneous data collection protocol. The sensor nodes possess varied energy levels. The selection of CHs is done based on the probability ratio between the residual energy of the nodes and average energy of the whole network. The possibility of evolving a CH is higher for the nodes which possess more residual energy. However, the probabilistic CH selection process prompts unequal clusters which leads to more energy dissipation.

Periodic, event-driven, and query-based protocol (PEQ) and its variation, CPEQ, were proposed by Boukerche et al. [35] in 2006. PEQ is designed for achieving the following: low latency, high reliability, and broken path reconfiguration. CPEQ is a cluster-based routing protocol. The publish/subscribe mechanism is used to broadcast requests throughout the network.

Genetic algorithm-based clustering approach (LEACH-GA) was introduced in literature [36] to predict the optimal probability for electing an optimal number of CHs. This approach improved the network lifetime by achieving energy-efficient clustering.

Artificial bee colony (ABC)-based algorithm [37] has been proposed, where the CH selection is performed by adopting the ABC algorithm. ABC algorithm improves the clustering process by employing efficient and fast search feature to select the CHs. Both cluster members to CH, and CH to BS communication is performed by direct data communication. However, this protocol does not consider the coverage of the CH and it prompts more energy dissipation.

Ant colony algorithm for data aggregation (DAACA) has been introduced by Chi Lin et al. [38]. This approach comprises of three phases: initialization, packets transmissions, and operations on pheromones. In the transmission phase, the next hop is dynamically selected by determining the number of pheromones of neighbor nodes and the residual energy. Pheromones' adjustments are accomplished for every specified number of rounds of data transmissions. Besides, various pheromones' adjustment strategies such as basic-DAACA, elitist strategy-based DAACA (ES-DAACA), maximum- and minimum-based DAACA (MM-DAACA), and ant colony system-based DAACA (ACS-DAACA) are utilized to enhance the network lifetime. However, duplication packets are transmitted from sink nodes to initialize the network, which causes higher energy depletion in the network.

Lusheng Miao et al. [39] have introduced network coding to resolve the issues in gradient-based routing (GBR) scheme, such as broadcasting of interest messages by sink node which prompts duplication of packets, which causes more energy dissipation, and point-to-point message delivery forces more data retransmissions due to the unstable network environment in WSNs. The authors have proposed network coding for GBR (GBR-NC) to implement energy-efficient broadcasting algorithm which reduces network traffic. Further, the authors have presented two competing algorithms such as GBRC and auto-adaptable GBR-C to minimize the data retransmissions.

In 2012, Rashmi Ranjan Rout et al. [40] proposed an energy-efficient triangular (regular) deployment strategy with directional antenna (ETDDA), where 2-connectivity pattern has been utilized. This pattern is accomplished by aligning the directional antenna beam of a sensor node in a specified direction toward the sink. Data forwarding depends on network coding for many-to-one traffic flow from sensor nodes to sink. The proposed approach ensures energy efficiency, robustness, and better connectivity in communicating data to the sink.

Ming Ma et al. [41] have put forward a mobility-based data-gathering mechanism for WSNs. A mobile data collector (M-collector), perhaps a mobile robot or a vehicle, is implemented with a transceiver and battery. The M-collector travels through a specific path and determines the sensor nodes, which comes within its communication range while traversing. Then, it collects the data from the sensor nodes in the single-hop communication and forward the data to the base station without delays. Hence, this mechanism improves the lifetime of the sensor nodes. The authors have primarily focused to reduce the length of each data-gathering tour called as single-hop data-gathering problem (SHDGP).

Roja Chandanala et al. [42] have presented a mechanism to preserve energy in flood-based WSNs by applying two techniques: network coding and duty cycling. Initially, the authors have proposed DutyCode, a cross-layer technique, where Random Low Power Listening MAC protocol was devised to implement packet streaming. The authors have applied flexible intervals for randomizing sleep cycles. Further, an enhanced coding scheme was proposed, which selects appropriate network coding schemes for nodes to remove redundant packet transmissions.

Meikang Qiu et al. [43] have introduced informer homed routing (IHR), which is a novel energy-aware cluster-based fault-tolerance mechanism for WSN. IHR is the foremost variant of dual homed routing (DHR) fault-tolerance mechanism. In this mechanism, each sensor node is attached with two cluster heads called primary cluster head (PCH) and backup cluster head (BCH). Sensor nodes deliver the data to PCH rather than sending simultaneously to both PCH and BCH. In each round, BCH probes the PCH to identify whether the PCH is active or not using the beacon message. In three continuous rounds, if BCH cannot receive any beacon message from PCH, then BCH will declare that the PCH has failed and it informs to sensor nodes to transmit data to BCH. Hence, IHR provides an energy-efficient fault-tolerance mechanism to prolong the lifetime of the network. However, cluster head selection process is containing more overhead.

A novel evolutionary approach for load-balanced clustering problem is presented in literature [44]. CH (gateway) formation is performed using a novel genetic algorithm. This algorithm differs from the traditional GA in the initial population and mutation phase. This approach balances the load among the gateways and it is energy efficient. However, sensor nodes that are not reachable to any gateway are left out from communication. Later, they extended a differential evolution-based approach [45] used for clustering the nodes with gateways (CHs) in a load-balanced way to ensure load balancing among the gateways and energy efficiency. But, this approach used single-hop communication between the gateway to BS and hence it may not be suitable for long-distance communication.

Flow partitioned unequal clustering (FPUC) algorithm has been proposed by Jian Peng et al. [46] to attain an enhanced network lifetime and coverage. FPUC has two phases: clustering and flow partition routing. In the clustering phase, cluster head is decided based on the higher residual energy and larger overlapping degree of sensor nodes. In the flow partition routing phase, cluster head collects the data from the member nodes and aggregates the data into a single packet; then it forwards the data to the sink through gateway nodes depending on residual energy The flow-partitioned routing phase has two subphases: dataflow partitioning phase and relaying phase. In the dataflow partitioning phase, the cluster head segments the dataflow into various smaller packets and then delivers these packets to its gateway nodes. In the relaying phase, gateways communicate the received data to the next hop with minimum cost.

An energy-efficient adaptive data aggregation strategy using network coding (ADANC) to attain improved energy efficiency in a cluster based duty-cycled WSN has been introduced by Rashmi Ranjan Rout et al. [47]. Network coding minimizes the network traffic inside a cluster and duty cycling scheme has been used in the cluster network to prolong network lifetime.

Dariush Ebrahimi and Chadi Assi [48] have presented a new compressive data gathering method. This method utilizes compressive sensing (CS) and random projection techniques to enhance the lifetime of large WSNs. The authors preferred the method to equally distribute the energy throughout the network rather than decreasing the overall network energy consumption. In the proposed data-gathering method, minimum spanning tree projection (MSTP) has been adopted. MSTP creates several minimum spanning trees (MSTs) and each root node of the tree aggregates sensed data from the sensor nodes using compressive sensing. A random projection root node with compressive data-gathering aids to achieve a balanced energy consumption all over the network. Besides, eMSTP has been introduced which is the extended version of MSTP; the sink node in the eMSTP behaves like a root node for all MST.

Ahmad et al. [49] proposed a protocol called Away Cluster Heads with Adaptive Clustering Habit (ACH^2) and this mechanism has been utilized for enhancing network lifetime. However, global node information is required for communicating data and the size of the clusters is also unequal. As the node distribution among the clusters is unequal, this approach prompts to variation in energy depletion ratio among clusters in the network.

A genetic algorithm-based approach [50] has been applied for binding the sensor nodes to the sink nodes, considering the balanced load among the sink nodes. The authors have presented a fitness function which takes into account the communication cost between the sensor node and sink node and the processing cost of the sink node. This approach dealt with the nodes which do not have any sink node in their communication range.

In 2015, energy-aware routing (ERA) [51] has been proposed, where the residual energy of the CHs and the intra-cluster distance are the parameters taken into account for the process CH selection. However, the parameters such as the optimal number of CHs, network density, and cluster coverage are not considered in the CH selection process; hence this causes uneven energy consumption in every cluster.

A GSA-based approach titled GSA-based energy-efficient clustering (GSA-EEC) was presented by literature [52]. For the fitness value calculation, the parameters considered are the distance between the sensor nodes and gateways, the distance between gateways and sink, and residual energy of gateways. This approach improves the network lifetime and total energy consumption. Further, they introduced a routing strategy titled gravitational search algorithm-based multi-sink placement (GSA-MSP) for placing multiple sinks on the sensor network [53].

Priority-based WSN clustering of multiple sink scenario using artificial bee colony [54] has been proposed. The fitness function in this approach considers the energy of the sink node and the sensor node, the distance between the sensor node to the sink node, and the priority of each sink.

PSO-based approach for energy-efficient routing and clustering has been proposed in literature [55]. Routing path between the gateway to BS is determined using the PSO technique. This approach provides energy-efficient routing and energy-balanced clustering. This approach is fault tolerant when CHs failed. But, nodes that are not reachable to any gateway are left out from communication.

Gravitational search algorithm for cluster head selection and routing (GSA-CHSR) [56] has been proposed. The authors have used GSA algorithm for deciding the optimal number of CH nodes and finding the optimal route between CH and BS. This approach improves performance parameters such as network lifetime, residual energy, and the number of packets received at BS. However, this approach incurs clustering overhead for selecting the optimal set of CHs.

Guravaiah and Leela Velusamy [57] proposed a routing protocol titled hybrid cluster communication using RFD (HCCRFD) based on clustering using river formation dynamics-based multi-hop routing protocol (RFDMRP) [58]. This protocol increases the network lifetime. However, load balancing among CHs is not considered and clustering overhead exists due to periodic CH selection. Further, the authors have proposed a balanced energy and adaptive cluster head selection algorithm (BEACH) [59]. They considered the parameters such as degree of the node, remaining energy of the node, the distance from BS to the sensor node, and the average transmission distance to its neighbors for achieving the load-balanced clustering.

Sl. No.	Algorithm	Techniques used	Metrics	Drawbacks
1	PEGASIS [31]	Chain construction	Lifetime	Network throughput decreased
2	LEACH [30]	Clustering	Lifetime, scalability	Not considering RE for CH selection, unbalanced energy consumption
3	TEEN [32]	Clustering	Lifetime	Same as LEACH, network throughput decreased
4	HEED [33]	Clustering	Lifetime	Direct transmission, heterogeneity is not considered
5	DEEC [34]	Clustering	Lifetime, scalability	Direct transmission, unequal size of clusters, unbalanced energy consumption
6	PEQ and CPEQ [35]	Clustering and publish/subscribe mechanism	Fault tolerance, low latency, and energy	Traffic overhead
7	DAACA [38]	Clustering, ACA	Energy, network lifetime	Bottleneck problem nearer to sink node, overhead in pheromones calculation at each round
8	GBR-NC, GBR-C, and auto-adaptable GBR-C [39]	Network coding and multi-hop	Network lifetime, energy	Transmission delays in competing algorithm
9	ETD-DA [40]	Directional antennas, network coding, and multi-hop	Energy, throughput, and low latency	Overhead in optimal antenna pattern and transmission power calculations
10	SHDGP [41]	Mobile collectors and single-hop	Energy, low latency, scalability, and throughput	High control overhead to maintain the trajectory path, packet loss due to speed of data collector
11	DutyCode and ECS [42]	Network coding, duty cycling, and multi-hop	Energy	Transition between active and sleep states overhead
12	IHR [43]	Clustering and multi-hop	Fault tolerance and energy	Node unable to find CH, leads to reliability problems
13	Novel evolutionary approach [44]	Clustering, genetic algorithm	Energy efficiency	Single-hop communication between the CH to BS
14	DE-based clustering algorithm [45]	Clustering using differential evolution	Energy efficiency	Single-hop communication between the CH and BS
15	FPUC [46]	Clustering, data aggregation, and multi-hop	Energy efficiency, lifetime	CH selection overhead
16	ADANC [47]	Clustering, network coding, and duty cycling	Energy, low latency, and lifetime	Cluster maintenance overhead
17	MSTP [48]	Data aggregation using compressive sensing	Energy, network lifetime	Computational overhead in MST calculations

Sl. No.	Algorithm	Techniques used	Metrics	Drawbacks
18	ACH^2 [49]	Clustering	Lifetime, throughput	Global node information for data transmission, cluster head selection overhead
19	GA-based approach [50]	Clustering using genetic algorithm	Energy efficiency	Single-hop communication between sink and BS
20	Energy-aware routing (ERA) [51]	Clustering	Energy efficiency, lifetime	Optimum number of CHs is not considered
21	GSA-EEC [52]	Clustering, GSA	Energy efficiency	Load balancing among CHs not considered
22	PSO-based routing [55]	Clustering (gateways) using PSO	Energy efficiency	Nodes that are not reachable to any gateway are not considered
23	GSA-CHSR [56]	Clustering using multi-hop GSA	Energy efficiency	Clustering overhead
24	HCCRFD [57]	Clustering using LEACH, RFD	Energy efficiency	No load-balanced clustering
25	BEACH [59]	Clustering, RFD	Energy efficiency	CH selection overhead
26	GSA-EC [61]	GSA, multi-hop	Network lifetime	Clustering overhead
27	Cuckoo and harmony search-based routing [63]	Cuckoo search algorithm	Energy efficiency	Load balance among CHs not considered
28	MLBC [64]	MOPSO, multi-hop, spanning tree	Energy efficiency, reliable	Nodes that are not reachable to any CH are not considered
29	Energy-efficient and delay-less routing [65]	FCR algorithm	Energy efficiency	Energy balancing is not ensured

Table 2.
Existing protocols for data collection.

An approach called LEACH-PSO [60] has been proposed for improving the network lifetime by selecting an optimum number of CHs in every round. In this work, the particle swarm optimization method is integrated with LEACH for forming the clusters.

Energy-efficient CH-based GSA (GSA-EC) [61] for finding an optimal set of CHs using GSA has been proposed. To balance the energy consumption, one-hop clusters are formed using an optimal set of CHs. The authors have also proposed the hybrid approach of PSO and GSA. This approach increases network lifetime and network stability. However, this approach also incurs clustering overhead for selecting the optimal set of CHs. Later, Kavitha et al. [62] used GSA for assigning sensor nodes to an appropriate cluster head (CH) in a load-balanced way such that it reduces the energy consumption and hence enhances the lifetime of a network.

Integrated clustering and routing protocol using cuckoo and harmony search has been proposed in literature [63]. This approach has adopted the cuckoo search algorithm for CH selection. Residual energy, degree of a node, intra-cluster distance, and coverage ratio are the parameters for developing fitness function used in CH selection. The harmony search algorithm has been employed for routing from

CH to BS. It is energy efficient and balances the energy consumption of the network. Further, it minimizes the un-cluster nodes, that is, nodes that are not within the communication range of any CH are minimized. But, load balancing among CHs is not considered.

Multi-objective load-balancing clustering technique (MLBC) [64] has been proposed for clustering in WSN by adopting multi-objective PSO (MOPSO) strategy which is used for CH selection. The shortest-path tree (SPT) for loop-free routing is created using Dijkstra's algorithm. It is energy efficient and reliable. But, the nodes that are not reachable to any CH are not considered.

In energy-efficient and delay-less routing [65], CH selection is performed using firefly with cyclic randomization (FCR) algorithm. This approach reduces transmission delay in the network. But, this approach has not considered energy balancing.

Overall comparison of above routing protocols are shown in **Table 2** with the techniques used, metrics considered, and drawbacks of each solution.

5. Future directions

Overall, the above discussed techniques' main objective is energy-efficient data gathering and is concentrated on the following issues:

- Duplication of data generation and forwarding
- Congestion or data storm problem nearer to the base station
- Selection of multi-hop routing path
- Operations to perform data aggregation
- Selection of cluster head

However, we need to concentrate on the following future directions for proposing new routing techniques:

- Almost all protocols require location information for routing. Location finding can be done using localization or GPS techniques, which are dependent on energy consumption. Finding of sensor location with less consumption of energy is an issue.
- Most of the multi-hop routing protocols suffer from overheads and delay due to path setup and relay nodes. Also, formation of loops in aggregate tree generation increases the energy consumption.
- Most of the literature failed in energy calculations at the time of CH selection in cluster-based routing protocols.
- Uneven distribution of cluster heads will generate unequal-sized clusters, unbalanced energy consumption between cluster members, and CH coverage problem.
- The size (with respect to area and number of members) inequality among the clusters leads to network coverage problem due to limited communication

range in large size (area) cluster and faraway nodes consume more energy in large size (area) cluster.

- The sizes of the clusters formed in the existing protocols are not equal. This leads to unbalanced energy consumption among the clusters.
- Density of network was not considered as a parameter in CH selection process. This impacts the formation of unequal sized clusters and leads to uneven distribution of load to CH.
- Uneven distribution of load on CH and the intra- and inter-communication path length is more.
- Security is the major parameter need to be considered in military applications. Considering security, energy efficiency is still challenging issues.
- In recent years, more popularity gain is deterministic rather than probabilistic-based clustering due to reliability. However, CH selection and other computational complexity are still a challenging area.
- Heterogeneous network in WSN is also an important problem due to different communication and processing capabilities.

6. Conclusions

In this chapter, classification of data collection routing protocols in WSN has been thoroughly discussed. Various techniques such as clustering, duty cycling, aggregation, network coding, sink mobility, and cross-layered solutions, and directional antennas have been utilized by data collection routing protocols for attaining long lifetime, energy efficiency, fault tolerance, and low latency. These techniques are reviewed briefly in this chapter. Finally, this chapter demonstrates a paramount comparison among the existing approaches applicable on data collection process in WSN. Future directions of routing protocols are presented at the end of this chapter.

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Chapter 7

WSN for Event Detection Applications: Deployment, Routing, and Data Mapping Using AI

Kamel Abbassi, Mohamed Hechmi Jeridi and Tahar Ezzedine

Abstract

In the 20th century, computers were senseless brains, but today, thanks to sensor networks, they can feel things for themselves. This major trend has given rise to many wireless sensor networks with the ability to sense the environment, deliver findings and process those data appropriately. Within this trend, this chapter outlines deployment and routing strategies as well as data handling practices. For convenience, the most encompassing application to consider is that of event detection.

Keywords: IoT, LLN, WSN, sensing, coverage, connectivity, deployment, routing, data fusion, machine learning

1. Introduction

Wireless sensor networks consist of many sensor nodes connected and providing valuable information for further processing to serve industry, people and society. The trend in WSNs is toward miniaturization, rapid deployment in large applications, reliable routing of data and its proper handling.

The broad description is based on four basic facts which are:

Capture: referring to the action of transforming an analog physical quantity into a digital signal. In our case, a study on the types of sensors seems necessary for the adequate choice for the application detection of events.

Concentrate and route: studying current routing techniques and refurbishing them to suit the event detection application.

Extract and Process: the data collected in their binary forms will be exploited through the use of AI techniques in perfect symbiosis with the proposed general architecture.

Store and Present: the fact of aggregating data, produced in real time, meta tagged, arriving in a predictable or unpredictable way, and the ability to restitute the information in a way that is understandable by Man, while offering him a means of acting and/or interacting.

2. Deployment issues

Identifying sensor node location and deployment strategies will be the first step toward building the network. Determination of sensor placement and rollout method depends on several criteria, mainly the intended applications, surrounding area, estimated deployment time and cost.

2.1 Nodes deployment and connectivity

2.1.1 Strategies of nodes deployment

Wireless sensor nodes may be enormously affected by node deployment. In fact, Wireless nodes deployment is able to extend network lifetime, efficient reliability and routing, well preserving of network energy, ensuring connectivity, etc. Placing nodes in a defined zone of interest is often not pre-determined at the outset of network layout and deployment. Indeed, the manner of how to locate the sensor nodes depends mainly on the application type and the operating conditions surrounding them. In WSNs, both random and deterministic methods of node placement can be applied [1, 2].

It should be noted here that roll-out can occur all at once or can be a continuous process where additional nodes could be redeployed in the given zone, thus two deployment strategies can be identified in WSN: uniform distribution and non-uniform one.

2.1.2 WSN connectivity

Communication modeling in low-power and lossy networks is difficult because nodes transmit at reduced power and radio links lack sufficient reliability. Hence, this research adopts the disk model as a deterministic communication method to ease the process of analytical computation [3, 4]. The model considers each wireless node "n_i" as being efficient in acquiring and transmitting data to nearby nodes. The communication range marked " R_i " is a function of the level of transmission power of a node. Accordingly, two nodes "n_i" and "n_j" can communicate with one another bilaterally only if the Euclidean distance there between is at least the minimum of their communication range (Eq. (1)).

$$d(n_i, n_j) \leq \min\{R_i, R_j\} \tag{1}$$

2.1.3 Detection in lattice WSNs

A network of wireless sensors is deployed in an area of interest for event detection, so each point in the area is covered by a sensor node if the Euclidean distance between the sensor node and this point is less than the sensing range R_S.

The probability that a sensor detects an event in the area of interest at a distance "d" is given by Eq. 2.

$$P(d) = \begin{cases} \mathbf{1} & \text{if } d \leq R_S \\ \mathbf{0} & \text{if } d > R_S \end{cases} \tag{2}$$

Due to the environmental and geographical conditions relative to the area of interest and manufacturers' requirements, we will define an uncertainty parameter "e" to make the model more realistic. Hence, the probability that a sensor will detect an event in the area of interest at a distance "d" is given by Eq. 3.

$$\boldsymbol{P(d)} = \begin{cases} \mathbf{1} & \text{if } \mathrm{d} < (\mathrm{R_S} + \mathrm{e}) \\ \boldsymbol{e^{-\alpha(R-R_S)^{\beta}}} & \text{if } (\mathrm{R_S} - \mathrm{e}) \leq \mathrm{d} \leq (\mathrm{R_S} + \mathrm{e}) \\ \mathbf{0} & \text{if } \mathrm{d} > (\mathrm{R_S} + \mathrm{e}) \end{cases} \tag{3}$$

α and β are the peripheral oriented parameters relative to the sensor node.

2.2 How detection and connectivity issues impact WSN coverage?

In deterministic deployment, sensor nodes are arranged around preset positions and carefully selected locations. Therefore, geometric shape designs can be adopted to form the coverage area as shown in **Figure 1**.

The firs purpose is to identify the appropriate number of sensor nodes to be deployed for full connectivity in the area in question.

Let "A" be the size of the AOI and "As" the area related to the sensor node's geometric configuration. The area of the geometric patterns of the sensor nodes is determined by knowing the length of the sides, designated by $\mathbf{l_x}$, i.e. $\mathbf{l_c}$ for the quadrilateral shape and $\mathbf{l_t}$ for the triangular one, and $\mathbf{l_h}$ for the hexagonal structure. Then, the estimated number of sensor nodes "N," is given by Eq. 4.

$$N = \frac{A}{A_S} \tag{4}$$

To have full connectivity, the pattern surface for each sensor node is given as follows:

$$As(\boldsymbol{con}) = \begin{cases} lc^2 = Rc^2 & \text{quadrilateral shape} \\ \frac{\sqrt{3}}{2} lt^2 = \frac{\sqrt{3}}{2} Rc^2 & \textit{triangular shape} \\ \frac{3\sqrt{3}}{4} lh^2 = \frac{3\sqrt{3}}{4} Rc^2 & \textit{hexagonal shape} \end{cases} \tag{5}$$

The number of sensor nodes adequate to ensure total connectivity is given by:

$$N(\boldsymbol{con}) = \begin{cases} \frac{A}{Rc^2} & \text{quadrilateral shape} \\ \frac{A}{\frac{\sqrt{3}}{2} Rc^2} & \textit{triangular shape} \\ \frac{A}{\frac{3\sqrt{3}}{4} Rc^2} & \textit{hexagonal shape} \end{cases} \tag{6}$$

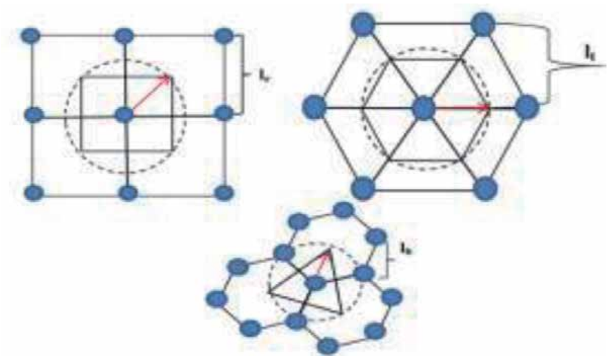


Figure 1.
Geometrical shapes of cover areas.

The second purpose is to identify the appropriate number of sensor nodes to be deployed to ensure total coverage; the geometric pattern surface relative to a sensor node is given by:

$$As(\boldsymbol{cov}) = \begin{cases} Rs^2 & \text{quadrilateral shape} \\ 3\dfrac{\sqrt{3}}{2}Rs^2 & \textit{triangular shape} \\ \dfrac{3\sqrt{3}}{4}Rs^2 & \textit{hexagonal shape} \end{cases} \tag{7}$$

The number of sensor nodes adequate to ensure total detection coverage is given by:

$$\boldsymbol{N}(\mathrm{cov}) = \begin{cases} \dfrac{\boldsymbol{A}}{\boldsymbol{Rs^2}} & \textbf{quadrilateral shape} \\ \dfrac{\boldsymbol{A}}{\dfrac{\mathbf{3\sqrt{3}}}{\mathbf{2}}\boldsymbol{Rs^2}} & \textbf{\textit{triangular shape}} \\ \dfrac{\boldsymbol{A}}{\dfrac{\mathbf{3\sqrt{3}}}{\mathbf{4}}\boldsymbol{Rs^2}} & \textbf{\textit{hexagonal shape}} \end{cases} \tag{8}$$

In harsh environments such as a battlefield or a disaster region, deterministic deployment of sensors is very risky and/or infeasible. In this case, random deployment often becomes the only option.

Providing connectivity within the network is a fundamental objective in wireless sensor networks for communication and data exchange between sensor nodes. A sensor is supposed to be connected if and only if it has a direct or indirect (multi-hop) communication path to a destination. For the sake of brevity, the explanation deals only with the case of a direct communication (a single jump) denoted 1-connected.

A wireless sensor network is said to be connected if all sensors are connected and if there is no isolated sensor in the network. Indeed, the number of its neighbors in its communication range R_C is called the “degree of sensor node.” It is in this sense that we will say that a sensor is isolated if its degree is equal to zero.

Consider arbitrarily a sensor in the network, the probability that it is isolated is equivalent to the probability that there is no neighboring sensor in its communication radius R_c, expressed in Eq. 9.

$$P_{iso}(S_i) = e^{-P\pi Rc^2} \tag{9}$$

The probability that the sensor S_i is not isolated is given by:

$$P_{non-iso}(S_i) = 1 - e^{-P\pi Rc^2} \tag{10}$$

If we consider that all sensors are deployed independently and uniformly in the area of interest, then they have the same probability of being non-isolated. Thus, the probability that there is no isolated sensor is as follows (Eq. 11)

$$P_{non-iso} = \prod_{i=1}^{N} P_{non-iso}(S_i) = \left(1 - e^{-P\pi Rc^2}\right)^N \tag{11}$$

The case where there is no isolated sensor in the network is required but not enough to say that this one stays connected. This gives us just the upper limit of the

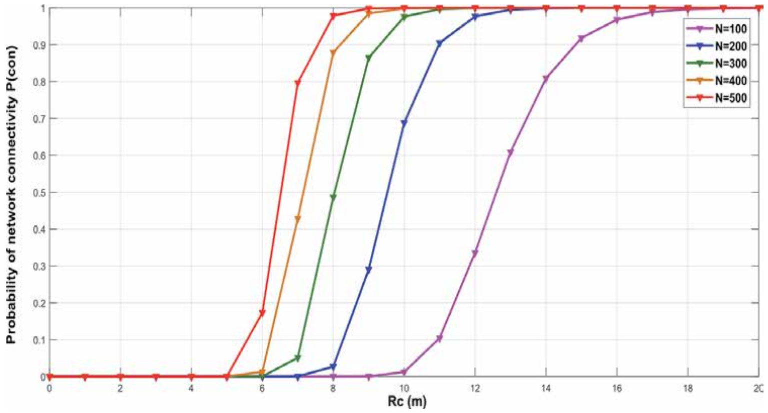


Figure 2.
Probability of network connectivity.

network connectivity. Also, the sensors need to have at least K neighbors in order to have K degree of connectivity in the network. In other words, a network in which all the sensors have at least one neighbor (i.e. there is no isolated sensor) implies that it is highly connected (high probability level of connection).

For more practical purposes we can consider a 100 m x 100 m area, changing the number of deployed nodes (from N = 100 to N = 500) and the coverage radius RC (from 0 m up to 20 m). Looking at the probability of network connectivity we can see that: there is a crucial communication radius over which a high probability of network connectivity exists. This radius is determined based on the configuration of the sensor nodes in accordance with the communication range as shown in **Figure 2**.

In this first section, we looked at the fundamental issues of wireless sensor network deployment, namely coverage and connectivity [5]. The first reflects the ability of the sensor network to provide detection in the area of interest and the second reflects the reliability with which the information collected by the sensor nodes will be transmitted for processing. But it is clear that the routing of data itself deserves to be properly considered for an appropriate sensor network dedicated to its intended application.

3. Toward proper routing

Routing data across nodes toward endpoints becomes the next logical priority, once deployment scenarios are dealt with.

Commonly, collected sensor data should be directed to a sink node via multi-hop routing. Certain applications may have different requirements, or constraints on the quality of the data transmission, such as end-to-end delay, jitter or churn, packet loss, etc. A set of constraints must always be respected. In fact, there are several proactive and reactive routing protocols that have been proposed for WSN [6]. One of them is the standardized proactive RPL (Routing Protocol for Low-Power and Lossy Networks), designed basically for “many to one” communications. A Destination Oriented Acyclic Graph (DODAG) is used for data collection, which is mainly a tree directed to the sink node. The calculation of the DODAG tree parameters is based on an objective function that is defined according to a single measurement. This section considers the use of RPL in WSN.

3.1 Purpose

Classically, self-powered, low-speed wireless personal area networks, such as 802.15.4, were considered unable to support IP. Now, 6LoWPAN and RPL made this possible. Even with the careful design of RPL routing, there is a need to assess this protocol in the context of more real-world applications.

In this section, focusing on a concrete application, that of event detection, we will assess the impact sending control packets at different time intervals, using different numbers of nodes and different transmission ranges. We will show how the variation of the control packet sending intervals can affect the performance of the routing protocol for low power lossy networks, considering the packet delivery rate and the power consumption.

3.2 Impact of network environment on the RPL

3.2.1 Preliminary details

RPL forms a Destination Oriented Directed Acyclic Graph (DODAG) (**Figure 3**), where each node has a rank calculated according to the cost metric and has a Preferred Parent (PP) as a gateway to the root [7]. In addition, RPL is regulated by three control messages ICMPv6 (Internet Control Message Protocol version 6) as defined in RFC 4443, namely:

- DODAG Information Object (DIO) which lets a node to discover an RPL instance,

- Destination Advertisement Object (DAO) allowing the propagation of destination information along the DODAG as well as the updating of the routing table on reception,

- DODAG Information Solicitation (DIS) for nodes that request to join the topology or to obtain more recent configuration information.

As for the objective function, it is indeed a mechanism enabling selection of the parent node by a child node, according to a metric of the DODAG tree. The main RPL specification does not have a built-in objective function, but both the zero-objective function (OF0) and the minimum order objective function with hysteresis (MRHOF) are recognized as defaulted OFs in this protocol [8, 9].

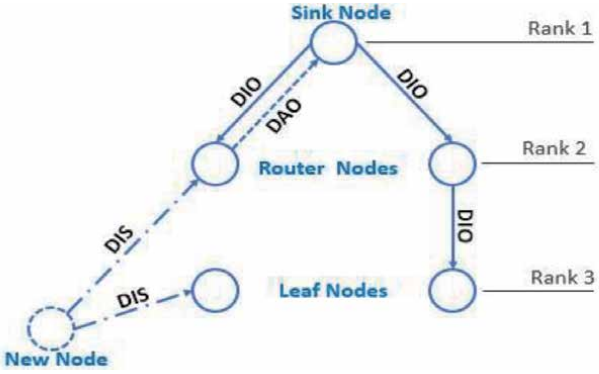


Figure 3.
DODAG Construction.

Proceeding with the actual data traffic handling arrangements, the analysis of the objective functions OF0 and MRHOF should be performed first. Indeed, OF0 is the Objective Function zero, which specifies how nodes select and optimize routes based on the minimum hop count to reach the parent node, while MRHOF stands for Minimum Rank with Hysteresis Objective Function which selects routes minimizing metrics, and uses hysteresis to reduce balancing in response to small changes in the metric.

To note that MRHOF works with Expected Transmission Count metrics (ETX) that are additive along a route and using the minimum rate to select the parent node and calculated according to Eq. (12).

$$ETX = \frac{1}{D_f \times D_r} \tag{12}$$

D_f denotes "forward delivery ratio" and indicates the likelihood of receiving the packet at the neighboring node.

D_r stands for "reverse delivery ratio" which calculates the probability of receiving the packet ack on receiver node side.

3.2.2 Procedures, tests, and evaluation

All simulations are carried out in the CONTIKI OS operating system using the Cooja simulator, considering the settings listed in **Table 1**. To perform the required simulations at various sending intervals (3 seconds, 5 s, 10s, 30s, 60s, 120 s, 300 s), we have modified the default parameter "PERIOD" in the "collect-common.c" file. Seeing that MRHOF is the default objective function for Contiki, we have modified the files rpl-conf.h and rpl-make. We had performed about 70 simulations in Cooja to evaluate the performance of the RPL objective functions in two scenarios.

Scenario 1: we fixed the network densities and modified the values of the TX range.

Scenario 2: we fixed the values of the TX range and modified the network densities.

In both scenarios, we have modified the sending intervals, allowing us to simulate highly constrained applications in lower SI values and normal applications in higher SI values.

In addition, a random topology will be used as this is the most suitable type chosen for the application. We implement a P2M topology, which means that there is only one sink node and the others are emitters, with a simulation time of about 10 minutes (600 seconds). The simulated platform was Tmote Sky under Unit Disk Graph Medium (UDGM) as the radio model. It should be noted that the Tmote Sky platform based on the MSP430 microcontroller with 10 KB of RAM and an

Settings	Value
Propagation model	UDGM with distance loss
Mote type	Tmote Sky
TX ratio	100%
Simulation time	600 seconds
Node position	Random

Table 1.
Used settings in the cooja simulator.

IEEE802.15.4 compatible radio is a constraint in the simulation of large networks because no more than 40 nodes can be simulated with reference to the hardware specification which leads to the limitation of the memory size of the routing tables [10]. The present work consists in testing the behavior of the two OFs in the RPL routing protocol by varying the SI sending intervals under various TX transmission ranges and different network densities. Following [11] the results of the simulation in the Cooja simulator could give the same results as in a practical experiment despite the external factors. Therefore, we will consider the Cooja results as practical tests. We collect all results obtained during all simulations and express them in graphs. We will discuss these results in subsections dealing only with each scenario.

Scenario 1: The network densities were set at 10 nodes and the Tx range values were varied from 50 m (**Figures 4** and **5**) to 100 m (**Figures 6** and **7**). It is clear that the longer the sending intervals, the lower the power consumption is in the case of OF0 and MRHOF, due to the fact that nodes consume more power since they send packets regularly and remain active in shorter intervals. Furthermore, Results indicate that MRHOF is more efficient than OF0 in terms of power consumption for one simple reason: MRHOF uses the ETX metric to build the routing table that reduces the amount of power used to transmit data between nodes.

The same conclusion for PDR, while increasing the sending intervals, the PDR value increases In fact, at tighter time intervals, nodes send packets repeatedly, leading to more load on delivered packets. Therefore, many packets do not reach destination because their capacity becomes exhausted. Thus, extending the send interval will increase the received packets, directly impacting the PDR value. Furthermore, we have noticed that when SI = 30s, MRHOF reaches 100% PDR. This could prove the idea that MRHOF performs better than OF0 in the PDR results because it reaches the full PDR ratio in fewer sending intervals.

Scenario 2: This scenario considers the TX range values at 100 m and changes the network densities from 10 nodes (**Figures 6** and **7**) to 15 nodes (**Figures 8** and **9**). Increasing the transmission intervals reduces power consumption. However, power consumption for OF0 and MRHOF are too close in this scenario, but MRHOF is still better.

We also notice that by increasing the network density, the power consumption increases compared to scenario 1, but the difference is not very important because we also increase the transmission range, so that more nodes reach the sink node

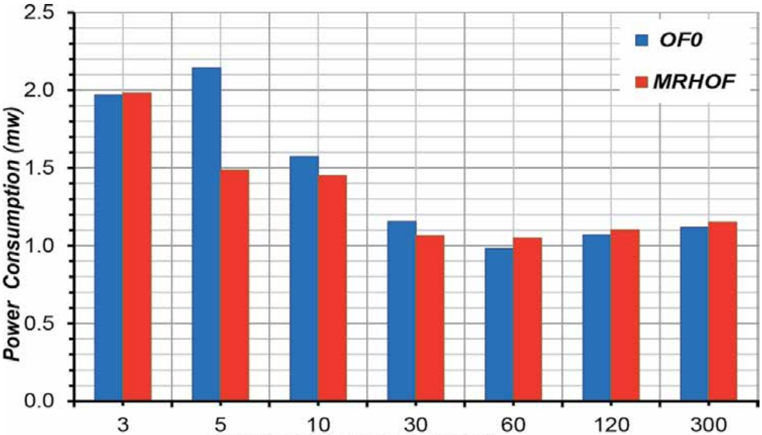


Figure 4.
Performance in power consumption (10 nodes, Tx = 50 m).

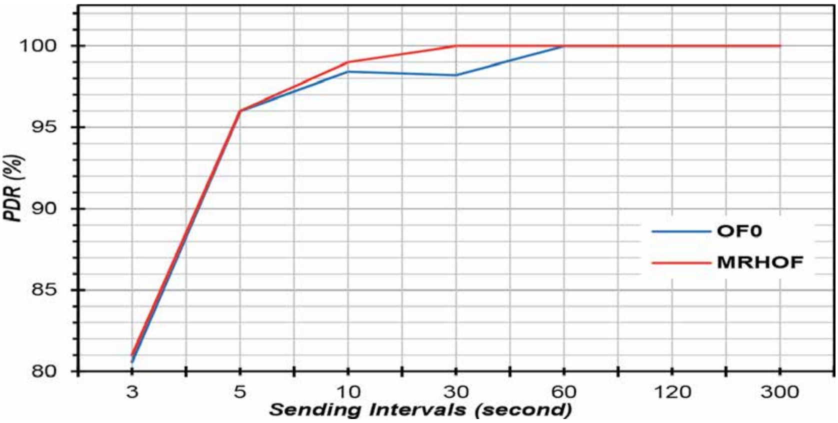


Figure 5.
Performance in PDR (10 nodes, Tx = 50 m).

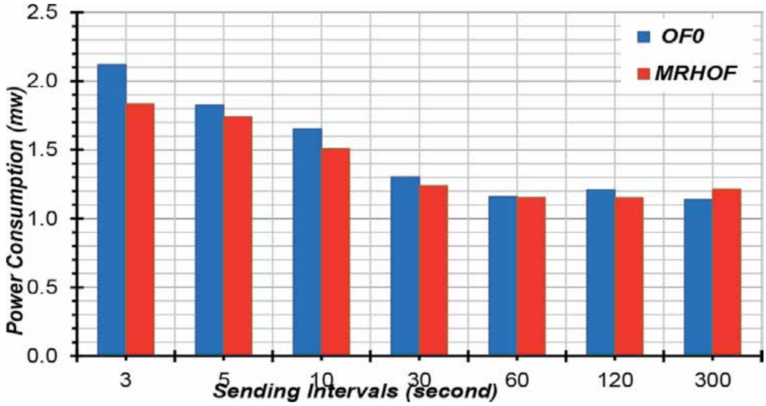


Figure 6.
Performance in power consumption (10 nodes, Tx = 100 m).

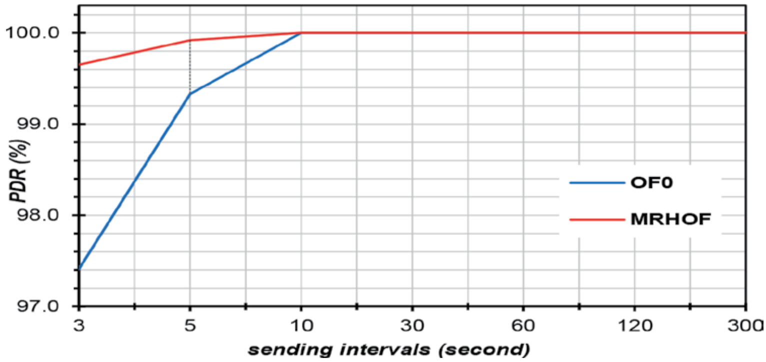


Figure 7.
Performance in PDR (10 nodes, Tx = 100 m).

without the need to switch from the transmitter to the receiver, thus lowering the power consumption level.

MRHOF reaches a higher PDR level in the former sending intervals, but OF0 is still not very performing and declined in 30 seconds of sending intervals due to

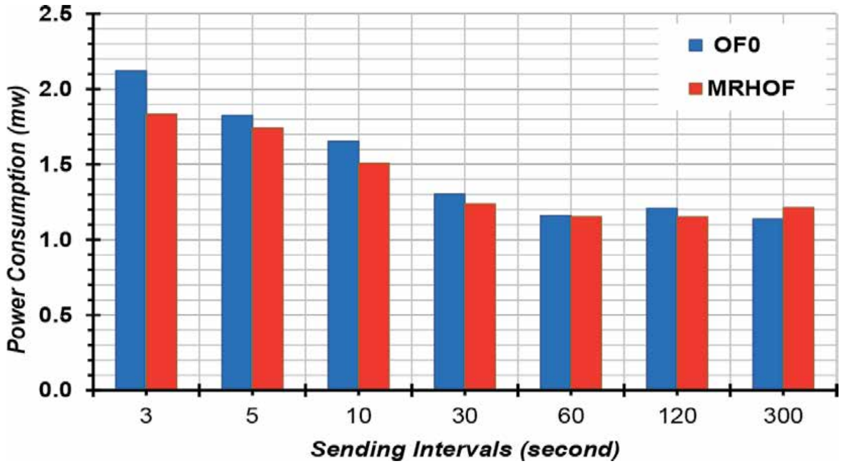


Figure 8.
Performance in power consumption (15 nodes, Tx = 100 m).

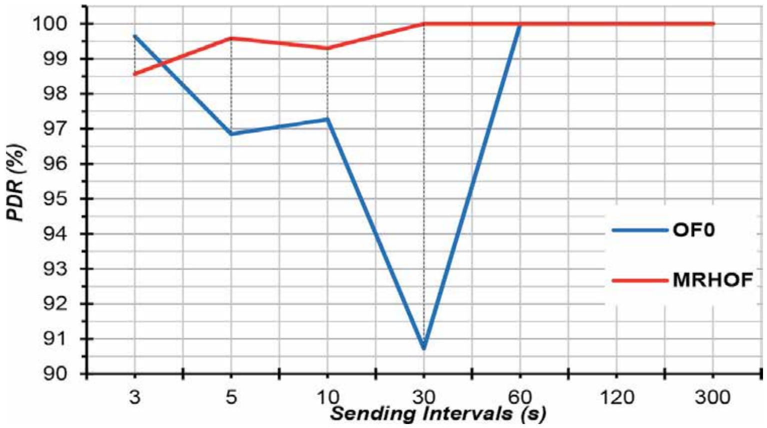


Figure 9.
Performance in PDR (15 nodes, Tx = 100 m).

inconsistent network structure, moreover not all nodes in this scenario were able to reach the destination node, what can be considered as unintended findings.

When we take the 60s as the value for the sending intervals, both MRHOF and OF0 had a 100% ratio for the PDR, confirming the fact that the PDR value increases as the sending intervals are incremented.

Finally, selecting an appropriate routing protocol to a given application like event detection is often important and necessary, however, it remains to be said that after the routing of data through the network, it is essential to process them correctly to benefit as much as possible from this content while keeping in mind the limitations of low capacity, low power and lossy networks. The following section outlines in more detail the proposed method for data treatment and mining.

4. Data querying and mining

Having carefully considered the deployment principles and the proper routing on the network, it remains to specify how to properly handle the data, most notably, if one considers WSN as a database. For the purpose of the event detection applications currently in use the processing of requests is a big challenge, so it is necessary to optimize the execution time and the resources used.

To reduce the cost of executing aggregated queries in event detection applications, events are often pre-calculated and materialized. These aggregated views are commonly known as summary tables that can be used to assist in responding to requests containing information beyond the view it represents. Yet, this provides a significant gain in performance. Many optimization techniques are available in the published work, such as indexing and fragmentation [12–14]. In this section, we consider materialized views.

4.1 Materialized view

The materialized views technique is mainly used to reduce the workload execution time [15]. It is made of several joints considered expensive to compute and store, especially for large sensor networks. It prepares these joints in the form of materialized views (MV) so that they do not repeat themselves each time. There are several algorithms to create the VMs such as backpack, similarity between queries, cache, etc. We will deal with the Jaccard similarity index approach [16]. The proposed technique as presented in **Figure 10** consists in:

- The extraction of the workload to create the query attribute table (each query is presented by a vector).
- Calculation of the similarity between each pair of vectors.
- For each similarity group we create a cluster (only clusters with high similarity will be kept).
- A view will be created for each cluster.

4.1.1 Modelization

The Workload Q is formed by n queries $\{Q_1, \ldots Q_n\}$. A query is composed by k attributes $\{a_1, \ldots a_k\}$, each query is $Q_i = \left\{a_j^i\right\}, \forall i : 1..n, j : 1..k$.

The activation function used in this work is:

$$f\left(a_j\right) = \begin{cases} 1 * a_j \textit{ if } a_j \textit{ used in } Q \\ 0 * a_j \textit{ else} \end{cases} \tag{13}$$

The workload can be presented in form of matrix:

$$MatA = \begin{pmatrix} a_1^1 * f(a_1) & \cdots & a_k^1 * f(a_k) \\ \vdots & \ddots & \vdots \\ a_1^n * f(a_1) & \cdots & a_k^n * f(a_k) \end{pmatrix} \tag{14}$$

The database management system has only one Final Solution *FS* (guarantees the re-joining to all workload with minimal cost). *FS* is formed by a set of materialized views v. Each view is composed of one or more attributes. Based on, N attributes, we can find $2^N - 1$ views and the *FS* has a view between 1 and $2^N - 1$.

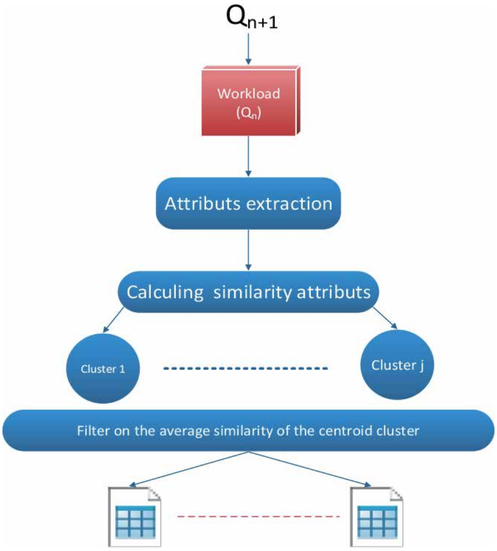


Figure 10.
Process of MV making.

$$FS^f = \left\{v_e^f\right\}, wheree \in \left(1..2^N - 1\right),\ f = \left(1..2^{2^N-1} - 1\right) \tag{15}$$

For example, FS^1 composed by $v_1, v_3, and\ v_4$:

$$FS^1 = \left\{v_1^1, v_3^1, v_4^1\right\} \tag{16}$$

In order to verify if this materialized view v_e is included in the solution FS^f or no, the function $h(v_e)$ having the following form should be used

$$h(v_e) = \begin{cases} 1, & v_e\ if\ v_e\ used\ in\ FS \\ 0, & v_e\ else \end{cases} \tag{17}$$

The maximum number of final solutions is $\left(2^N - 1\right)^{2^N-1}$.

The final solutions are presented as follows

$$FS = \begin{pmatrix} v_1^1 * h(v_1) & \cdots & v_{2^N-1}^{\left(2^N-1\right)^{2^N-1}} * h\left(v_{2^N-1}\right) \\ \vdots & \ddots & \vdots \\ v_1^n * h(v_1) & \cdots & v_{2^N-1}^{\left(2^N-1\right)^{2^N-1}} * h\left(v_{2^N-1}\right) \end{pmatrix} \tag{18}$$

The references of the final solutions are stored in a vector VS (19).

$$VS = \left\{S_f\right\}, where\ f = \left(1..2^{2^N-1} - 1\right) \tag{19}$$

The sizes based on the final solutions are illustrated in **Figure 11**, where:

The first level illustrates all the attributes $\{a_1, .., a_n\}$ in the database tables.

The second level represents all the possible pointers of the materialized views i.e., $\{v_1, .., v_{2^n-1}\}$.

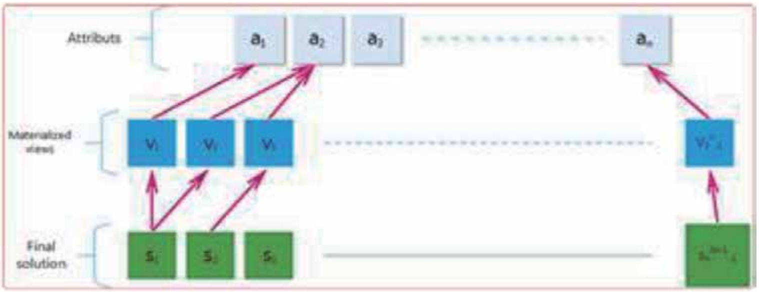


Figure 11.
Final solutions tree.

The third level presents all the possible final solutions where *FS* can be formed by one or all the materialized views. Thus, the maximum number of final solutions is $2^{2^n-1}-1$.

4.1.2 Learning practice

Our learning system consists of an input layer serves to receive the *MatA* matrix, an output layer to receive the *FS* matrix, and hidden layers (**Figure 12**). The $\{MatA, \ FS\}$ present the learning set. For each *MatA* input, the learning network gives a *FS* as a response.

The network is presented by the Eq. (20).

$$\mathrm{F} = \mathrm{G}(\mathrm{MatA}, \mathrm{W}), \textit{where W is the input weights} \tag{20}$$

Learning is defined by the process used to find $\hat{W}$ for all MatA such as $FS \cong \hat{FS}$, where FS and $\hat{FS}$ represent respectively, the final solution and the desired weight. Thus, the error function $Err(MatA, FS, W)$ (21) measuring the Euclidean distance between the MatA and output *FS* must be minimized.

$$Err(MatA, FS, w) = \|MatA - FS\|^2 = \sum_{i=1}^{n} (MatA_i - FS_i)^2 \tag{21}$$

The relationship between query-attributes Matrix and Final solutions matrix is given by Eqs. 22 and 23.

$$MatA * W + \beta = FS \tag{22}$$

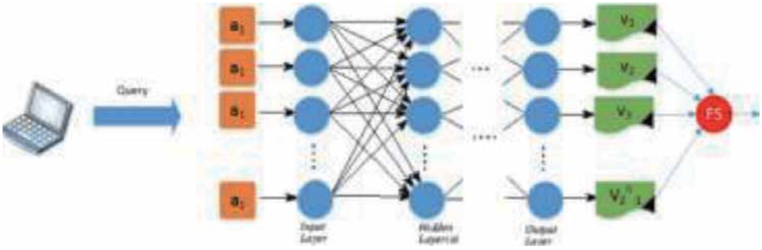


Figure 12.
Artificial neural network to create MVs.

Otherwise:

$$\begin{pmatrix} a_1^1 * f(a_1) & \cdots & a_k^1 * f(a_k) \\ \vdots & \ddots & \vdots \\ a_1^n * f(a_1) & \cdots & a_k^n * f(a_k) \end{pmatrix} * \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} + \beta = \begin{pmatrix} v_1^1 * h(v_1) & \cdots & v_{2^N-1}^{(2^N-1)^{2^N-1}} * h(v_{2^N-1}) \\ \vdots & \ddots & \vdots \\ v_1^n * h(v_1) & \cdots & v_{2^N-1}^{(2^N-1)^{2^N-1}} * h(v_{2^N-1}) \end{pmatrix} \tag{23}$$

Note: β is the bias.

4.2 Algorithms

The proposed approach is structured in two algorithms, the one for generating VMs and the other for their prediction.

Algorithm 1: ***Building VMs***

```
Input: Q: Workload, LP: learning period, Aused: Attributes used in Q, A: Attributes set
Output: FS: Final solution
*/ Final solution = materialized Views set */
Setup:
A: array () array of pointers of all attributes defined in the database
V: array () of pointers of all possible materialized views
FS: array () of pointers of all possible final solutions
Start
While (counter < LP) {
    Aused ← extraction(Q)
    MatQA ← query_attributes(Aused,Q)
    MatJS ← Jaccard_similarity (MatQA)
    Graphs ← graph (MatJS)
    Views ← cluster (Graphs)
    Training_views (MatA, FS)
    Counter ++
}
FS ← prediction_views(Q)
End
```

Prior to the start, the training period must be tested (**Figure 13**). Once it is running, the algorithm follows the usual processes by creating the attributes of the query matrix and finding similarities between each vector.

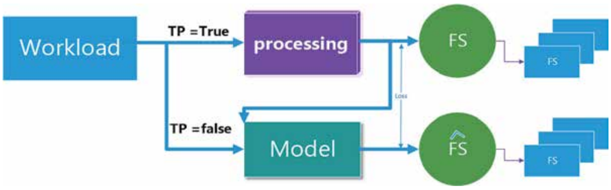


Figure 13.
Switching between the training phase and the prediction phase.

Algorithm 2: ***Predicting VMs.***

```
Input: Qn + 1: next query, W: weight given by learning algorithm
Output: Final solution (Materialized Views set)
Begin
A = Extraction (Qn + 1)
Views = A*W
Return Views
End
```

The complete process of creating MVs with the learning machine is illustrated in **Figure 14**.

First, all attributes used in the database tables are identified then every possible solution with the corresponding MV will be generated. Here only references for views are generated, the real MVs can be created in the learning step using Jaccard similarity technique. We identify the MVs per solution within this learning phase so as to find their optimal resolution. The neural network considers the attributes and views obtained when building the model. Once this learning step done, the optimal solution with the attributes present in the Qn + 1 workload will be found by the model.

4.3 Test and result

Concrete case examples will be considered to make the tests and deduce the results.

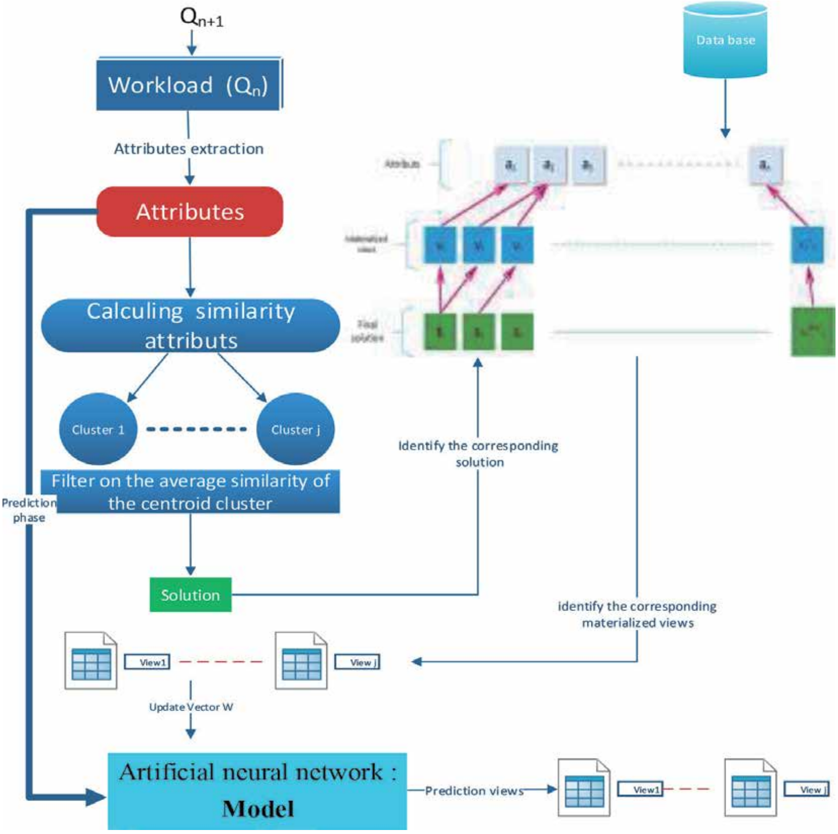


Figure 14.
Global architecture.

Initialization:

Considering a workload composed of seven queries $\{Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7\}$ and five attributes $\{a_1, a_2, a_3, \ a_4, \ a_5\}$.

To proceed, store all the attributes in a list (**Figure 15**).

Next, a table composed of all possible MVs gets formed (**Figure 16**).

References set of materialized views

Then, all the references for the possible final solutions (PFS) will be created (**Figure 17**). In our test example, PFS = $2^{2^5-1} - 1 = 2147483647$.

Training phase:

Without being too sophisticated, three times {T1, T2 and T3} will be used in the example and we will measure the input weights W then we will present the experimental results of our approach

- **At time T1**, with one query $Q = \{Q_1\}$

	Q1
a1	1
a2	1
a3	0
a4	1
a5	1

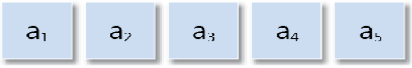
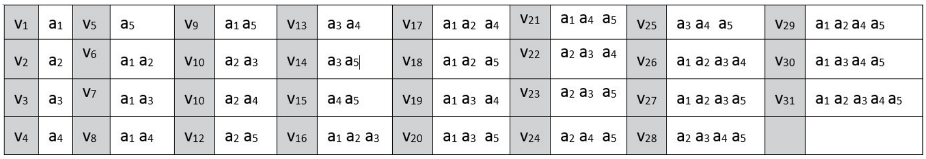


Figure 15.
Example of attributes set.



V1	a1	V5	a5	V9	a1 a5	V13	a3 a4	V17	a1 a2 a4	V21	a1 a4 a5	V25	a3 a4 a5	V29	a1 a2 a4 a5
V2	a2	V6	a1 a2	V10	a2 a3	V14	a3 a5	V18	a1 a2 a5	V22	a2 a3 a4	V26	a1 a2 a3 a4	V30	a1 a3 a4 a5
V3	a3	V7	a1 a3	V10	a2 a4	V15	a4 a5	V19	a1 a3 a4	V23	a2 a3 a5	V27	a1 a2 a3 a5	V31	a1 a2 a3 a4 a5
V4	a4	V8	a1 a4	V12	a2 a5	V16	a1 a2 a3	V20	a1 a3 a5	V24	a2 a4 a5	V28	a2 a3 a4 a5		

Figure 16.
References set of materialized views.

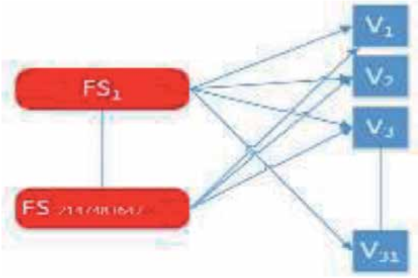


Figure 17.
Final solution references.

We need to set a matrix showing the similarity between two attributes with Jaccard Index JI. For example, $a_1 = (1\,1\,1\,1\,1\,1\,0)$ and $a_2 = (1\,1\,1\,1\,1\,0\,1)$ is computing as follow:

$$J(a_1, a_2) = \frac{a_1 \cap a_2}{a_1 \cup a_2} \tag{24}$$

J (a1, a2) = J (a1, a4) = J (a1, a4) = J (a2, a4) = J (a2, a5) =1, J (a1, a3) = J (a2, a3) = 0.

Only the pairs of attributes having a similarity > = 0.5 will be considered. The attributes having a similarity equal to 1 will be ignored. We can divide the attributes into 1 graph $C_1 = \{a_1, a_2, a_3, a_4, a_5\}$. The average similarity value for each centroid cluster is computed as follow: $(C_i)_{avg} = \frac{\sum_{j=1}^{2^n} J(a_i, a_j)}{2^n}$ where i $\neq$ j, $J(a_i, a_j)$ in Jaccard index between $a_i and a_j$. If the average similarity value is more than 0.5, the graph is considered a cluster. In this case, (C1) avg. = 1, {a1, a2, a4, a5} is a set of attributes exist in V29, where the final solution is FS29.

Then, finding $W = (w_1, w_2, w_3, w_4, w_5)$ with the following equation

$$1 * w_1 + 1 * w_2 + 0 * w_3 + 1 * w_4 + 1 * w_5 = 29 \tag{25}$$

	Q_1	Q_2
a_1	1	1
a_2	1	1
a_3	0	1
a_4	1	1
a_5	1	1

- **At time T2** with two queries: $Q = \{Q_1, Q_2\}$

J (a1, a3) = 0; J(a2, a3) = J(a3, a4) = J (a3, a5) = 0.5;
J(a1, a2) = J (a1, a4) = J (a1, a5) = J (a2, a4) = J (a2, a5) = J (a4, a5) = 1;
Graph C1 = {a2, a3, a5};
Graph C2 = {a1, a2, a4, a5}
(C1)avg = {J(a2, a3) + J(a2, a5) + J(a3, a5) }/3 = (0.5 +1+ 0.5) / 3
= 0,666667;
(C2)avg ={J(a1, a2) + J(a1, a4) + J(a1, a5) + J(a2, a4) + J(a2, a5) + J(a4, a5)}/6= 1;
{a2, a3, a5} ⇔ V23;
{a1, a2, a4, a5} ⇔ V29.
According to (17), we have:
FS1 ➔ V1 … FS31 ➔ V31; FS32 ➔ V1 V2 … FS61 ➔ V1 V31; FS91 ➔ V3 V4 … FS118 ➔ V3 V31; … FS466 ➔ V23 V29
So, we calculate $W = (w_1, w_2, w_3, w_4, w_5)$ with the following equation

$$2 * w_1 + 2 * w_2 + 1 * w_3 + 2 * w_4 + 2 * w_5 = 466 \tag{26}$$

	Q1	Q2	Q3
a1	1	1	1
a2	1	1	1
a3	0	1	1

a4	1	1	0
a5	1	1	0

- **At time t3** $Q = \{Q_1, Q_2, Q_3\}$

J (a3, a4) =*J* (a3, a5) =1/3; *J* (a1, a2) = *J* (a4, a5) =1
J (a1, a3) = *J* (a1, a4) = *J* (a1, a5) = *J* (a2, a3) = *J* (a2, a4)
=*J* (a2, a5) =2/3;
Graph C1 = {a1, a2, a4, a5} where similarity = 1
Graph C2 = {a1, a2, a3, a4, a5} where similarity = 1
(C1) avg. = (*J* (a1, a2) + *J* (a1, a4) + *J* (a1, a5) + *J* (a2, a4) + *J* (a2,a5) + *J* (a4, a5))/ 6 = 1;
(C2) avg. = (*J* (a1, a2) + *J* (a1, a4) + *J* (a1, a5) + *J* (a2, a3) + *J* (a2, a4) + *J* (a2, a5) + *J* (a3, a4) + *J* (a3, a5) + *J* (a4, a5))/9 = 6/9.
{a1, a2, a4, a5} ⇔V30;
{a1, a2, a3, a4, a5} ⇔V31
V30 and V31 exist in final solution FS496
We calculate $W = (w_1, w_2, w_3, w_4, w_5)$ *with the following equation*

$$3 * w_1 + 3 * w_2 + 2 * w_3 + 2 * w_4 + 2 * w_5 = 496 \tag{27}$$

5. Result

The host computer of the simulations runs under Linux Ubuntu 16.04 and has an Intel(R) xenon(R) CPU E5-2640 v4 processor running 2.4 GHz × 2.4 GHz (2processors) with 128 GB of memory. All the algorithms were implemented in Python 3. After a learning period, the experimental results (**Figure 18**) show a reasonable decreasing between the real solution and the prediction.

The part data mapping using AI was the final part of a quite complete process, beginning with sensors placement followed by the data routing till their smooth handling where we used the business intelligence to create materialized views in a dynamic processing. A mathematic approach has been proposed to present the workload and the attributes used. Next, we introduced our proposed methodology, split into two algorithms. The first is a neural network used for learning using

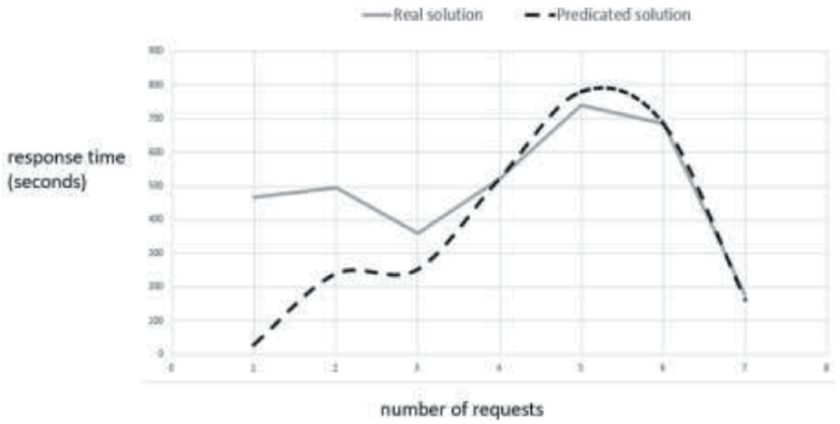


Figure 18.
Real solution vs. predicted solution.

similarity between attributes to provide a model to be used a second time. For the second algorithm, the network model is used to predict the future solution.

6. Conclusions

A wireless sensor network is a network of distributed autonomous devices that can cooperatively detect or monitor physical or environmental conditions. WSNs are used in many applications such as environmental monitoring, habitat monitoring, natural disaster prediction and detection, medical monitoring, and structural health monitoring, which we have encompassed in this work through the application event detection or fact detection. WSNs consist of a large number of small, inexpensive, disposable, autonomous sensor nodes that are typically deployed on an ad hoc basis over large geographic areas for remote operations. Sensor nodes are severely limited in terms of storage resources, computing capacity, communication bandwidth and power supply, which is why the decision was made to perform heavy computing outside the WSN network in computing centers. Indeed, the sensor nodes are grouped into clusters, and each cluster has a node that acts as the cluster head. All nodes transmit their sensor data to the cluster head, which in turn routes it to a specialized processing node(s) via multi-hop routing. In event detection applications, nodes detect the environment and immediately evaluate the data to determine its usefulness. If useful data (an event) is detected, the data is transmitted to the base station(s). Data traffic is difficult to predict events typically occur randomly and the resulting data traffic is sporadic. However, an amount of data must be exchanged for route management and network controls, even if no events are detected. A wireless sensor network, can, contrastingly, be considered as an intelligent, scalable system for monitoring and sensing the physical world's properties. In the last few years, the database research and development community claimed that if one considers a WSN as a database (which means that an essential feature of its smart design is the ability to perform explicit requests), this could lead to a considerable savings in the development of software engineering that runs a data acquisition program for the wireless sensor network, as well as a very favorable cost-effectiveness ratio due to the optimization of data queries. This work outlines a query computing model for the wireless sensor network that meets many of the requirements of considering the WSN as a database.

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Chapter 8

Swarm Intelligence-Based Bio-Inspired Framework for Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) are gaining immense popularity as a result of their wide potential applications in industry, military, and academia such as military surveillance, agricultural monitoring, industrial automation, and smart homes. Currently, WSN has garnered tremendous significance as it is has become the core component of the Internet of Things (IOT) area. Modern-day applications need a high level of security and quick response mechanism to deal with the emerging data trends where the response is measured in terms of latency, throughput, and scalability. Further, critical security issues need to be considered due to various types of threats and attacks WSNs are exposed to as they are deployed in harsh and hostile environments unattended in most of the mission critical applications. The fact that a complex sensor network consisting of simple computing units has similarities with specific animal communities, whose members are often very simple but produce together more sophisticated and capable entities. Thus, from an algorithmic viewpoint, bio-inspired framework such as swarm intelligence technology may provide valuable alternative to solve the large scale optimization problems that occur in wireless sensor networks. Self-organization, on the other hand, can be useful for distributed control and management tasks. In this chapter, swarm intelligence and social insects-based approaches developed to deal with a bio-inspired networking framework are presented. The proposed approaches are designed to tackle the challenges and issues in the WSN field such as large scale networking, dynamic nature, resource constraints, and the need for infrastructure-less and autonomous operation having the capabilities of self-organization and survivability. This chapter covers three phases of the research work carried out toward building a framework. First phase involves development of SIBER-XLP model, Swarm Intelligence Based Efficient Routing protocol for WSN with Improved Pheromone Update Model, and Optimal Forwarder Selection Function which chooses an optimal path from source to the sink to forward the packets with the sole objective to improve the network lifetime by balancing the energy among the nodes in the network and at the same time selecting good quality links along the path to guarantee that node energy is not wasted due to frequent retransmissions. The second phase of the work develops a SIBER-DELTA model, which represents Swarm Intelligence Based Efficient Routing protocol for WSN taking into account **D**istance, **E**nergy, **L**ink Quality, and **T**rust **A**wareness. WSNs are prone to behavior related attacks due to the misbehavior of nodes in forwarding the packets. Hence, trust aware routing is important not only to protect the information but also to protect network performance from degradation and protect network resources from undue consumption. Finally, third phase of the work involves the development of SIBER-DELTAKE hybrid model, an improved ACO-KM-ECC trust aware routing protocol based on ant colony optimization technique using K-Medoids (KM) algorithm for the formation of clusters with Elliptical Curve Cryptography (ECC). KM yields efficiency in setting up a cluster head and ECC mechanism enables secure routing with key generation and management. This model takes into account various critical parameters like distance, energy, link quality, and trust awareness to discover efficient routing.

Keywords: wireless sensor networks, swarm intelligence, ant colony-based routing, node misbehavior, non forwarding attacks, pheromone update model, reputation system, trust aware routing, K-Medoids clustering algorithm, ECC based secure routing, energy balancing, network life maximization

1. Introduction

WSN is an emerging research area that promotes wireless communication across the nodes in a network in a random fashion. A huge set of parameters relevant to natural weather conditions pertaining to spatial and temporal domains is prominent to assess the performance of WSNs. Hence, in comparison with the normal ad-hoc networks, WSN exhibits more restricted constraints and critical conditions. WSNs are designed with a wide variety of sensors designed to tune in consistent with the particular application based domain. In WSNs, each node is mostly equipped with a restricted battery, a rather tiny memory unit, a simple processing unit, and a radio transceiver. Communication through these devices leads to the actual fact that a sensor network is a wireless ad-hoc network. Each sensor node generally supports multi-hop routing where nodes act as forwarders, relaying data packets to sink or a base station. Apart from monitoring the environment, the biggest challenge posed in WSN is the computation capability. Some of the algorithmic issues that need to be tackled in a sensor network are routing, object tracking, data gathering, power saving, base station initiated querying, etc. Solutions to the aforementioned problems hence demand an innovative computing paradigm [1].

One of the main challenges in WSNs is the large scale networking that is the sheer size exhibited by the wireless sensor networks. WSNs have an extensive collection of present and future applications ranging from a few hundred to several hundred thousand, comprising of low-end sensor nodes. The first direct consequence of such a large scale is the huge amount of traffic load incurred across the network. This could easily exceed the network capacity, and hence, hamper the communication reliability due to packets loss by collisions and congestion along the chosen path to the destination from the event field [2]. The other major aspect to deal with WSNs is the growth of the network, which impacts the overall performance and functionality. In such a scenario, it becomes essential to find the optimal routes and to maintain the communication overhead at tolerable levels when data broadcasting over a large network. This plays a prominent role to assess the scalability aspect of WSN in terms of time and space complexity. As the network scales up, the routing tables and traffic to maintain these tables also increase. For this reason, networking systems must be adaptive and scalable to variation in the size of the network. Bio-inspired mechanisms such as Ant Colony Optimization (ACO) techniques provide efficient routing mechanisms for large-scale mobile ad-hoc networks. Another major challenge to be considered is the dynamic nature of WSNs. Early communication systems comprising of transmitter/receiver pairs and communication channel are all static, whereas current networking systems are dynamic due to their node behavior, mobility, bandwidth channels, demand patterns, traffic and networking conditions. It is essential to take into account the communication mode adopted across the nodes within a particular range to estimate the overall network quality. In a target tracking application, the amount of traffic generated may increase or decrease with the time which depends upon the target behavior and monitored area. This imposes a varying load on the network resulting in inefficient capacity utilization if static approaches are used. To solve this problem, the bio-inspired solutions are known to be proficient in adapting themselves to changing circumstances towards survival.

The ability to deal with resource constraints also adds up to a major challenge in WSNs. As the number of resources acquired by the nodes increases, the overall cost in terms of bandwidth utilization also increases. More specifically, for the WSNs composed of nodes that are inherently constrained in terms of energy and communication resources, these limitations directly bound their performance and mandate for intelligent resource allocation mechanisms. The biological systems help researchers by providing solution approaches to deal with the trade-off between high demand and a limited supply of resources. For example, in the foraging process [3], ants use their individual limited resources towards optimizing the global behavior of colonies in order to find a food source in a cost-effective way. The behavior of ant colonies in the foraging process inspires many resource-efficient networking techniques. The need for autonomous operation without infrastructure also contributes to a major challenge in WSNs. Infrastructure free environment calls for a mechanism to track the growing number of nodes in the network to overcome adverse impact of overall network failure. The performance of the network must be assessed before and after every operation executed either statically or dynamically across the network so that networks continue their operations without any interruption due to the potential failures. This adds up a major responsibility on the network towards self-organization, self-evolution, and survivability. In order to tackle these challenges, biological systems provide promising solutions in the context of WSNs.

Swarm Intelligence is based on the study of the collective behavior of distributed and self-organized systems such as ant colonies, swarms of bees or birds, flocks of fishes. Ant colonies exhibit interesting characteristics which are most desirable in the context of WSN management and control. Ant colonies are able to effectively coordinate themselves to achieve specified global objectives without centralized planning or organizational structure. These cooperative behaviors to accomplish the complex tasks emerge from individual ant's much simpler behaviors and local rules which they follow by instinct. It is evident that the adaptability, flexibility, and robustness exhibited in their behaviors made them capable to solve real-world problems. In the literature [4, 5], several routing protocols with various metrics that use ant colony optimization have been reported. Ant colony optimization is a meta-heuristic approach inspired by the behavior of real ants seeking the path from their colony to the food source. Real ants explore the possible paths between a food source and their colony by depositing pheromones on their return journey to the colony and then follow the shortest path, that is, the path having the highest pheromone trails from colony to the food source. ACO is used to find the optimal path from the source (nest) to the destination (food). Forward ants select the next node randomly. Upon reaching the destination, the forward ant gets converted into backward ant and deposit pheromone trail on the path traversed. The pheromone trail will be more on the shortest path towards food. Here, the mechanism implied by the ants is said to be either random probability based or a heuristic based approach. If the mechanism followed by an ant is found to be successful, then it is adopted; else it is discarded and another path is discovered.

Secure routing is highly demanding in Wireless Sensor Networks due to the nature of routing operation in an infrastructure less environment wherein resource-constrained nodes need to cooperate with each other to route the packets. For most of the mission-critical applications, WSNs are to be deployed in harsh and hostile environments unattended where critical security issues need to be considered due to various types of threats and attacks they are exposed to. In addition to the robust key management schemes used to secure the network from external attacks [6], WSN requires strategies to mitigate the effect of insider attacks by detecting the misbehavior nodes refusing to participate in packet delivery thereby launching non-forwarding attacks. These behavior related attacks can be thwarted by assigning trust rating to nodes in the network based on the reputation they build over a period of time by being trustworthy in participating in the packet delivery. There are several insider attacks or behavior level attacks that target the routing operation in WSN [6]. In the black-hole attack, adversary nodes do not forward packets completely, whereas in a gray-hole attack, malicious nodes selectively forward some packets. Most of the insider attackers are Denial of Service (DOS) attacks [7]. Behavioral level attacks can be mitigated by providing trust enabled routing to prevent non-forwarding attacks by insider misbehaving nodes. Identity-related attacks can be avoided by providing security services based on efficient cryptography approaches to secure data confidentiality and data integrity. The various routing attacks possible against WSN can be stated as follows: Worm Hole Attack where in there is a threat on confidentiality and authenticity; Denial of Service attack (DoS) attack, where there is a threat on the availability, integrity, confidentiality and authenticity; Selective forwarding attack, which creates threat towards availability and integrity; Sink hole, gray hole and Sybil attacks posing threat on availability, integrity and authenticity; Carousel attacks holding a threat on availability, confidentiality and authenticity. Hence, there is a need to use appropriate techniques to protect data and overall network functionality from the aforementioned attacks. The number of packets dispatched correctly from source to destination, the number of packets lost, the amount of energy consumed, the fake addresses generated during the routing process, etc. are various parameters to be considered to deal with WSN attacks.

Most of the conventional networking paradigms are unable to accommodate the scalability, complexity and heterogeneity of modern world real-time scenarios. These challenges are new by-products of evolution in communication technologies in the last few decades. Hence, there is a need to identify the mechanisms that perform suitably well when dealing with a huge set of nodes, with dissimilar behavioral aspects. Particularly when dealing with WSN for insect colonies, individual node responses account for more loads and degrade the performance of the overall network. Hence, to achieve optimality in terms of resource utilization and scalability, there is a need to switch from static to dynamic access strategy. At the other end, the characteristics such as adaptive to the varying environmental circumstances, robust and resilient to failures caused by internal or external factors and self-organization lead to different levels of inspiration from biological systems towards deriving different algorithm approaches and designs at network layer for effective, robust and resilient communication. Majority of the work in the literature captures the laws of dynamics to deal with aforementioned scenarios in the modern world that may result in a probabilistic outcome. The common rationale behind this research is to capture the governing dynamics and understand the fundamentals of biological systems in order to devise new methodologies and tools for designing and managing WSNs that are inherently adaptive to dynamic environments, heterogeneous, scalable, self-organizing and evolvable. Many of the existing works in literature in the WSNs area focus on achieving better outcomes in terms of energy efficiency or optimal routing paths based on the shortest distance or scalability aspect to deal with a huge crowd of packets and nodes or distance based minimization with limited security aspects. In this work, various essential parameters like distance, threshold, energy, link quality with security are integrated to achieve productive outcomes across the network traversal. These solutions are addressed in the proposed methodology in the form of SIBER-XLP with TECB, SIBER-DELTA, and SIBER-DELTAKE.

This chapter is organized as follows—Section 2 provides brief review on the related work in the area of swarm intelligence based secure and trust enabled energy efficient routing for WSNs. Section 3 discusses the SIBER-XLP model which represents Swarm Intelligence Based Efficient Routing protocol for WSN with Improved Pheromone Update Model and Optimal Forwarder Selection Function. This section also presents the Threshold Energy Conservation and Balancing (TECB) approach developed in SIBER XLP model for static and dynamic environments. Section 4 proposes SIBER-DELTA model which is Swarm Intelligence Based Efficient Routing protocol for WSN with Distance, Energy, Link Quality, and Trust Awareness designed to suit the harsh and hostile environment where the WSN nodes are deployed. Section 5 presents SIBER-DELTAKE model, an improved ACO-KM-ECC trust aware routing protocol based on ant colony optimization technique using K-Medoids (KM) algorithm for the formation of clusters and setting up of cluster heads, and Elliptical Curve Cryptography (ECC) mechanism for secure routing with key generation and management which further takes into account Distance, Energy, Link Quality and Trust Awareness in the routing decision. In this hybrid model, both the identity and behavior related attacks are tackled with effective results depicting the overall performance of the proposed work. This is followed by a section on conclusion and future research directions.

2. Related work

Swarm Intelligence area, on which the routing protocols of WSN are based, leads to optimal use of resources in a distributed way. The routing capacity of a protocol is effective if it leads to the minimization of energy and cost of traversal across the nodes. Swarm intelligence based efficient routing (SIBER) is an Ant Colony Optimization (ACO) [8] based routing algorithm for WSN where the forward ants are launched at regular intervals from source node with the mission to locate the sink node with equal probability by using neighbor nodes with minimum cost along the path from source to sink. ACO in integration with WSN achieves better energy saving and reduction in communication overhead. Using variants of the basic ACO, several approaches with different constraints were proposed in the area of ACO based routing algorithms for WSN. In the Energy Efficient Ant Based Routing (EEABR) Protocol proposed in [9], pheromone distribution is used in such a way that nodes nearer to the destination have high pheromone when compared to the other nodes. It suffers from excessive packet delivery delay as it does not take into account link quality. IEEABR [5] is an improved version of EEABR which allows non-optimal paths to be selected for packet transmission, increasing network lifetime and preserving network connectivity, but incurs excessive delay in packet delivery. Sensor Driven and Cost-Aware Ant Routing (SC), Flooded Forward Ant Routing (FF) and Flooded Forward Ant Routing (FF) protocols are proposed in [10]. The SC algorithm is energy efficient but suffers from a low success rate. Flooded Forward Ant Routing, FF Protocol is a multipath routing protocol which uses broadcast method to route packets to the sink by flooding forward ants to the sink. The FF algorithm exhibits shorter time delays, but suffers from generation of significant amount of traffic. Flooded Forward Ant Routing, FF Protocol utilizes constrained flooding of both forward and data ants to route the data and to discover optimal paths. It exhibits high success rate when compared to SC and FF but suffers from high energy consumption. It has been seen from the detailed analysis of various-reported ant colony based routing algorithms for WSN in the literature [4, 5], most of the ant colony based routing techniques do not consider all the parameters to select the best quality path in terms of energy, distance, link quality and other metrics thereby leading to the selection of sub-optimal paths. WSNs form a major source for Internet of Things (IoT) due to their ability to adapt dynamically with the modern world gadgets. The computational capacity of a sensor network depletes while progress is made to transmit data across the nodes in a network. Hence the protocols to route data across the network need to be highly dynamic in nature with the ability to adapt to changes in the environment. Clustering relevant data into similar entities, ability to reduce the size of data by applying mining techniques, increasing the network life time in a robust fashion, dealing with power and network outages across widely distributed geographical locations are some of the parameters that need to be considered while the development of the routing algorithms.

A Reputation system based framework for Energy Efficient, Trust-enabled Secure Routing for Wireless Sensor Network proposed in [10, 11] incorporates a customized reputation system defined as Sensor Node Attached Reputation Evaluator (SNARE). SNARE is a collection of protocols that communicates directly with the network layer and adopts geographical routing principle to cope up with large network dimensions and relies on a distributed trust management system for the detection of malicious nodes. The system consists of three main components—monitoring component, rating component and response component. The monitoring component, observes packet forwarding events. Here a monitoring node will not be in a continuous monitoring mode of operation, rather, it will monitor the neighborhood periodically and probabilistically to save resources. When a misbehaving event is detected, it is counted and stored until an update time and then a report is forwarded to the rating component. The rating component at the other end, evaluates the amount of risk an observed node would provide for routing operation. The risk value is a quantity that represents the previous misbehaving activities that a malicious node (a node that drops packet) obtained. This value is used as an expectation for how much risk would be suffered by selecting that malicious node as a router. Risk values are updated based on the first hand information every time a new misbehavior report is received from the monitoring component. Additionally, if an observed node behavior is idle for a certain period of time, then its risk value is reduced. A monitoring node also updates the risk values of its neighbors by second hand information received periodically from some announcers. Based on the trust relations, a node will try to avoid malicious nodes based on the routing decision made by the routing protocol—Geographic, Energy, Trust Aware Routing protocol (GETAR) [11]. GETAR incorporates the trust information along with distance and energy information (routing decisions are based on a weighted routing cost function which incorporates trust, remaining energy and location attributes) to choose the best next hop for the routing operation thus allowing for better load balancing and network lifetime extension. To design a framework based on reputation for sensor networks, nodes maintain reputation for other nodes and use it to evaluate their trustworthiness. This results in the development of a robust and scalable model in a generalized fashion to deal with defects across the data transmission process. This approach employs Bayesian formulation where probability is of at most significance. Social networking plays a prominent role to determine the trust factor based on reputation of a node. The present and future behavior of nodes in the network can be judged based on the reputation of a particular node [12]. Beta reputation based system is a strong inference based system that enables to set foundation of trust between the people in e-biz world. The performance of such a system can be evaluated by changing the weight across the nodes (small or large), by changing the feedback factor (positive or negative), by changing the discount and forgetting factors (old or new), and an integration of either of these factors, all based on reputation factor of a node. The goodness of this approach is that it is not adhered to any single environment [13]. However, as it also uses probability to calculate the aforementioned parameters, the working of this system cannot assure effective results in real time.

At the other end, authentication and key management schemes are the most important security services to provide data security and data confidentiality in WSN. Techniques such as random key pre-distribution for pair wise key establishment and broadcast authentication to provide security without the expensive Public key cryptography operations is preferable for deployment in traditional networks. However, random key pre-distribution techniques cannot ensure key establishment among any two nodes and endure arbitrary node compromises at the same time. Moreover, it has become highly challenging task to achieve loose time synchronization required by all broadcast authentication schemes in WSNs [14]. In recent years, application of Public key cryptography on resource-restricted sensor networks in the form of Elliptic Curve Cryptography (ECC) has emerged as highest preferred approach among several PKC options as a result of its fast computation, small key size, and compact signatures. ECC is based on mathematical formulation of discrete logarithmic problem that performs scalar computations among the points on the curve. With this kind of computation, it is difficult for the intruders to extract the original message in WSN environment. ECC uses discrete log approach to generate key and to perform encryption and decryption techniques. A data packet can be encrypted using ECC upon discovery of route to the sink node [15]. ECC is further strengthened by the addition of a predetermined threshold values in the method that transmits the information by splitting the original information into several small pieces of information, based on which the appropriate secret key will be generated, making it difficult for third parties to tamper over the network. This method was found to be effective as compared to RSA algorithm for sensor networking environment. However, the size of message piece was chosen in random, without describing any standard methodology to achieve effective threshold based outcomes [16]. An efficient integrity-preserving data aggregation protocol yields better performance in terms of reduction of the communication overhead as compared to the modulo addition based methods. This integrity preserving method in conjunction with Elliptic Curve Cryptography results in achieving the maximum optimum higher bound in a secure way. The proposed work in [17] allows the verification of the authenticity of aggregated data both at the base station and aggregators. However, due to the decryption at aggregators, both these approaches suffer leakage of data privacy. Also, the method developed is applicable to hierarchical structures with level wise arrangement. The algorithm proposed in [18] to construct the optimal network architecture in a cluster form employs Elliptic Curve Cryptography to commute public and private keys using a 176-bit encryption key consisting of combining the node ID, Elliptic curve encryption key, and the distance to its cluster head. Homomorphic encryption is used to allow cluster head to aggregate the encrypted data without having to decrypt them thereby reducing the energy consumption of cluster heads. This proposed technique greatly improves the network lifetime, memory requirements, communication overhead, and energy consumption. The ECC can in turn be integrated with other Message Authentication Code (MAC) to enhance the level of security through authentication [19].

WSNs where the sensor nodes combine their data to form a global environment include base stations that process the data collected across various nodes. This may result in depletion of huge amounts of energy and scalability issues. The solution to overcome this problem is through integration of clustering algorithms. Various heuristic based clustering methods that enable the reduction in energy consumption include linked clustering, hierarchical clustering and weighted clustering algorithms like highest connectivity based clustering, Max-Min Clustering, LEACH method, etc. The linked clustering algorithms like LCA and LCA2 work well in the scenarios where there is a unique identity assigned to each node in the cluster. However, there may be limited number of clusters or nodes per cluster, making it difficult to work in dynamic environment [20]. In Highest Connectivity clustering method, the cluster head is selected based on the highest degree of a node. The clusters once chosen to act as a master may in turn act as a slave if new cluster head is elected. At the other end, in max-min clustering, stable masters and large clusters can be created with huge set of messages delivered across each node from source to destination. In weighted clustering algorithm, the mobility and transmission energy of a node enable to elect a cluster head. Large amount of energy is consumed as the cluster head is selected based on the combined weight of each node. In Low Energy Adaptive Clustering Hierarchy (LEACH) and Two Level LEACH, cluster head is chosen dynamically with local computation being carried out at each node. At the other end, distributed cluster head is elected at consuming more power in Energy Efficient Clustering Scheme. There is little or no control over the cluster head in this clustering method. In Power Efficient Gathering in Sensor Information Systems (PEGASIS), large number of nodes in a cluster can be formed, which leads to high energy efficiency but leads to long delays when the chain (huge number of connected nodes) is long. In our proposed model, k-medoids clustering is chosen that overcomes the drawbacks of the aforementioned methods, as the appointment of cluster head is done based on the distance of the data points from cluster center and hence there is no consumption of higher energy or dissipation of high power, resulting in constant performance across the nodes suitable for wireless sensor networking environment. The selection of a cluster head varies from one protocol to the other, with probability based approach being the most common one to estimate the energy level and power consumption level of a particular node in heterogeneous environment [21]. Efficient routing technique is regarded as the one that develops shortest path between the cluster head and sink, leading to the development of optimal path. Also, the energy consumption of sensor nodes in WSN can be minimized using clustering techniques where nodes with similar properties form a cluster and are close in resemblance to each other. The election of a cluster head in various clustering techniques can be made based on either a probability model or a fuzzy rule selection [22]. Fuzzy logic is built around a set of inference rules that enable to measure various parameters like distance, probability, density of a node, etc.

3. SIBER-XLP model

This section deals with the proposed model SIBER-XLP: Swarm Intelligence based Efficient Routing for WSN with Improved Pheromone Update Model (PUM) and Optimal Forwarder Selection Function (FSF). SIBER-XLP model considers the link quality of the path along with energy and distance to select the shortest path from source to destination. It has been observed from our detailed analysis of various reported ant colony based routing algorithms for WSN that the Forwarder Selection Function to select a node for packet forwarding and Pheromone update model need to be revisited. SIBER-XLP includes two variants named as SIBER-ELP having Equal Link Probability signifying the routing scheme for sensor nodes deployed in Normal Environment like schools, hospitals, commercial organizations etc., and SIBER-VLP having Variable Link Probability signifying the routing protocol for sensor nodes deployed in Harsh Environment like defense, battle fields etc. Depending on the environment where they are deployed and the prevailing networking conditions, it is noticed that link quality and other related parameters may vary which are not taken into account when selecting the next forwarder by various ant colony based routing algorithms for WSN in the literature as in [4, 5, 8, 9, 21–23]. By considering these problems into account, the proposed work in this section suggests an improved FSF, in order to select the best next neighbor to forward the packet to the sink node. It is also observed that the PUM model varies from one algorithm to another as the parameters used in the computation of the amount of pheromone concentration to be placed on the path traversed by the backward ant differ. Further, it is found that the amount of pheromone computed to be placed on the path during return journey is not proper to reflect that path as an optimal one, during the simulation period. In general, a strongest path must have more pheromone when compared to weakest path and the variations in pheromone concentration should be such that always strongest path is selected. Keeping these considerations in mind, PUM model is designed with the metrics—minimum and average energy of the nodes along the path, number of hops (i.e., distance indicating shortest path), and link quality of the path, which are collected during their journey from source to sink.

3.1 Proposed SIBER-XLP architecture

The proposed model SIBER-XLP [24] consists of two main components FSF and PUM. In this architecture, a node to traverse considers the path of its neighbors on both the sides and then proceeds accordingly based on various control parameters like alpha (α), beta (β) and gamma (γ). The SIBER-XLP architecture is depicted in **Figure 1**.

3.1.1. Forwarder selection function (FSF)

FSF uses a probabilistic approach at every node along the path from source to sink node in the network to select the best next neighbor to forward the packet to

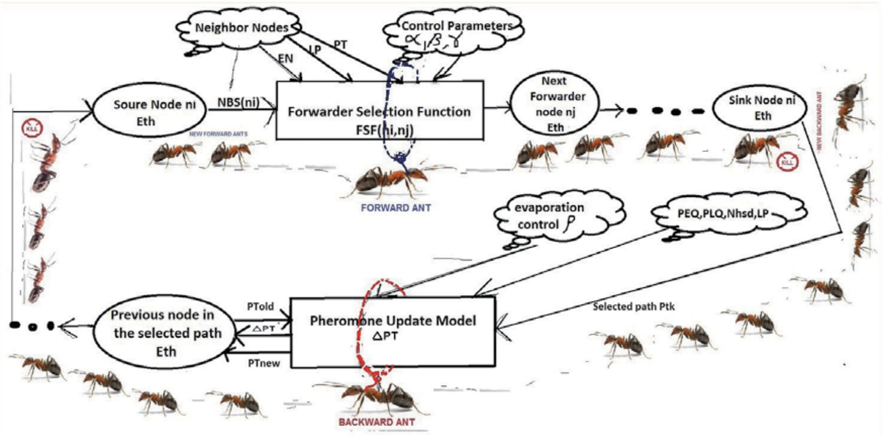


Figure 1.
SIBER-XLP model architecture.

the sink node. The Forwarder Selection Function must always choose an optimal path from source to the sink to forward the packets with the sole objective to improve the Network Lifetime by balancing the energy among the nodes in the network to ensure that some nodes along the path do not get depleted fast (resulting in Network disconnections or partitioning) and at the same time selecting good quality links along the path to guarantee that node energy is not wasted due to too frequent retransmissions. Further, selection of shortest paths involving less number of nodes results in saving of energy due to the participation of few set of nodes in packet forwarding. FSF uses a probabilistic approach to select the best node among neighboring nodes to forward the information based on Pheromone Trail (PT), Node Energy level (EN) and node link quality (LP). PT function represents the concentration of pheromone deposited on the path between the nodes, that is, current node and its neighbor node considering Energy, distance and link quality along the path from source to destination. In other words, higher PT represents the better quality path from source node to the destination in terms of energy, distance and link quality. EN function represents the energy level of the neighbor node and LP function represents the quality of the link between the current node and the neighbor node.

Hence, FSF (n_i, n_j)selects the best node $n_j$among neighboring nodes to forward information from the current node n_i can be defined as:

$$FSF(n_i,n_j) = \left\{ \begin{array}{l} \dfrac{[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}}{\sum_{j \in NBS(n_i)}[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}}, if j \in NBS(n_i), \\ 0, otherwise, \end{array} \right\} \tag{1}$$

where $NBS(n_i)$ represents the set of neighboring nodes of n_i, $PT(n_i,n_j)$ represents the amount of pheromone trail between the nodes n_i&n_j, $EN(n_j)$ represents the energy associated with the neighbor node n_j. $LP(n_i,n_j)$ represents the link quality between nodes n_i&n_j or link probability.

Link Probability $LP(n_i,n_j)$ between nodes n_i&n_j is given by the expression:

$$LP(n_{i,}n_j) = \frac{1}{ETX(n_i,n_j)} \tag{2}$$

where *ETX* is an Expected Transmission Count, calculated based on the past events occurred along that link. α, β,γ are the tunable parameters to control the importance of node energy level, pheromone trail, and link quality of the path. When α = β = γ = 1, all three parameters *PT*, *EN*, *LP* are given equal importance in the selection of the forward node. If higher priority is to be assigned to *PT* that represents pheromone trail of the path, then assign the values as α = 1, β = γ = 2. Likely, to prioritize *EN* level of node, assign the values as α = 2, β = 1, γ = 2. Finally, to give high priority to *LP* parameter, assign the values as α = 2, β = 2, γ = 1 in the selection of forward node.

Let $EI(n_j)$ be the node n_j—initial energy and $ER(n_j)$ be the node n_j—remaining energy; then energy level of the node n_j, $EN(n_j)$ is given by:

$$EN(n_j) = \frac{ER(n_j)}{EI(n_j)} \tag{3}$$

where

$$ER(n_j) \succ E_{th}$$

Threshold Energy $E_{th}$is associated with each and every node.E_{th} is defined as the minimum threshold energy needed for a node to participate in packet forwarding. Another possibility provided is to set E_{th} to the least minimum threshold ($E_{th_{\min}}$) at which point the nodes will discontinue in packet forwarding because of energy exhaustion or detachment from the network.

3.1.2. Pheromone update model (PUM)

It is observed that the amount of pheromone computed to be placed on the path during return journey is not efficient to reflect that path as an optimal one, during the simulation period. Strongest path should have largest amount of pheromone whereas weakest path should have least amount of pheromone or almost zero. Among the competing stronger paths for selection, the variations in pheromone concentration should be such that always strongest path (i.e., optimal) is selected. Taking this into consideration, improved PUM model with the following parameters collected by the forward ant is developed—E_{avg}, Average energy of the nodes involved in the path traveled by forward ant, $E_{\min}$, Minimum energy of the nodes involved in the path traveled by forward ant, Nh_{sd}, Number of hops from source to sink traveled by the forward ant, $LP(Pt_k)$, Link Probability of the nodes involved in the path from source to sink traveled by the forward ant. Average ETX of the links in the path Pt_k, is given as:

$$ETX_{avg}(Pt_k) = \frac{\sum_{i=1}^{Nh_{sd}(Pt_k)} ETX_i}{Nh_{sd}(Pt_k)} \tag{4}$$

$$\text{Link quality of the path } Pt_k, LP(Pt_k) = \frac{1}{ETX_{avg}(Pt_k)} \tag{5}$$

$$\text{Path Link Quality}, PLQ(Pt_k) = \frac{LP(Pt_k)}{Nh_{sd}(Pt_k)} \tag{6}$$

$$\text{Path Energy Quality}, PEQ(Pt_k) = \frac{E_{avg}}{E_{in}} - \left(1 - \frac{E_{\min}}{E_{avg}}\right) \tag{7}$$

Higher average and minimum energy of nodes along the traversed path would result in a good quality path in terms of Energy.

Pheromone Update Function,

$$\Delta\text{PT} = \text{PathEnergyQuality} * \text{PathLinkQuality}$$

$$\Delta PT = \left(\frac{E_{avg}}{E_{in}} - \left(1 - \frac{E_{\min}}{E_{avg}}\right)\right) * \frac{LP(Pt_k)}{Nh_{sd}(Pt_k)} \tag{8}$$

Equation (8) extracts the impact of average and minimum energy of the nodes along the optimal path. In other way, good quality optimal paths having high average and minimum energy will result in large amount of pheromone deposition on the path. If destination node is reached, then forward ant is converted to backward ant and the traversed path is updated by improved Pheromone Update Function (ΔPT).

At instances where nodes nearer to the destination are supposed to have higher pheromone deposition as compared to the nodes nearer to source, ΔPT computed in (8) is updated by the backward ant in the following fashion:

$$\Delta PT = \Delta PT * \left(1 - \frac{Nh_{cd} - 1}{Nh_{sd}}\right) \tag{9}$$

where Nh_{cd} is the number of hops from current node to the destination node during the traversal of backward ant from destination to the source node.

Whenever a node n_i receives a backward ant coming from a neighboring noden_j, it updates $PT(n_i, n_j)$ in its routing table in the following manner:

$$PT(n_i, n_j) = (1 - \rho)PT(n_i, n_j) + \Delta PT \tag{10}$$

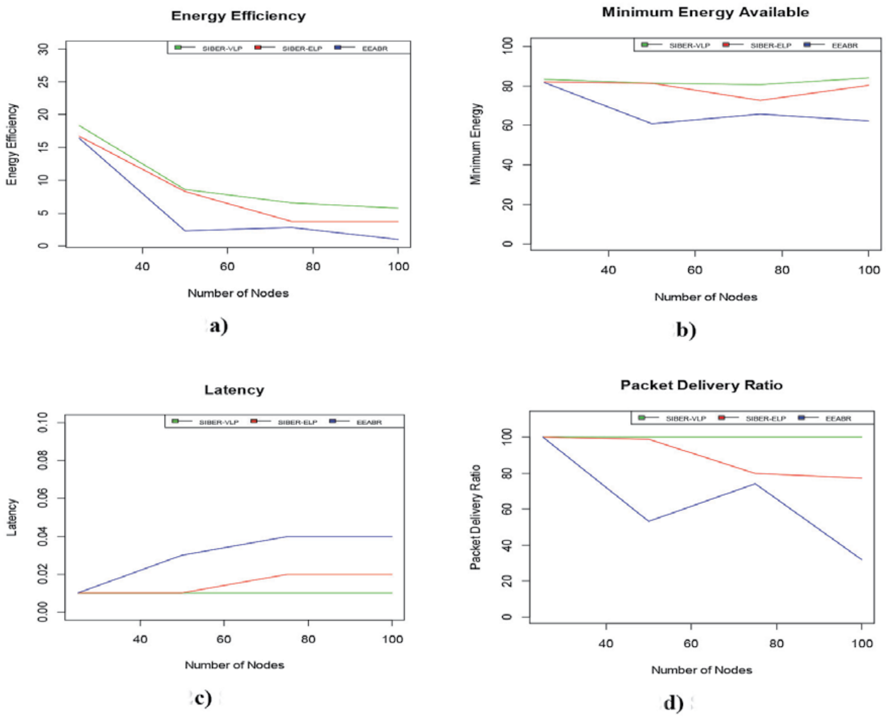
where, ρ is a decay coefficient and (1- ρ) represents the evaporation of Pheromone trail since the last time $PT(n_i, n_j)$ was updated.

3.2 Performance evaluation

SIBER-XLP model with static and dynamic deployment of nodes is implemented and simulated using NS-2. To evaluate the performance of proposed model, initial scenario with random network topology is chosen to carry out the experiment with random way point mobility model selected to progress at a specified speed. The network size with 25, 50, 75 and 100 nodes is considered to demonstrate the effectiveness of results. The results obtained by the implementation of the proposed work are compared against the existing EEARB model in [9] to evaluate the efficiency of the proposed work. The parameters chosen to determine the effectiveness of the proposed model are Energy efficiency abbreviated as EE, Minimum Available Energy represented as ME, Latency shown as LT, Packet Delivery Ratio represented as PDR. The behavior of nodes in static and dynamic environments against parameters EE, ME, PDR, LT is shown in **Figures 2** and **3**. The results show the effectiveness of SIPER-VLP model against the other models like SIBER-ELP and EEABR for a maximum of 100 nodes. **Figures 2(a)** and **3(a)** show a significant increase in energy efficiency for both SIBER-ELP and SIBER-VLP models when compared with EEABR in static environment, while still showing greater increase in energy efficiency in dynamic environment. As evident from **Figures 2(b), (d), and 3(b)**, **(d)**, the PDR and ME values are more in dynamic than in static mode and have much higher value compared to EEABR. It is observed from the **Figures 2(c)** and **3(c)** that the latency variation is similar irrespective of the kind of environment in which the nodes are deployed. From the simulations results, it is clear that SIBER-VLP recording best performance over EEABR and SIBER-ELP recording average performance as compared to SIBER-VLP but better than EEABR model.

3.3 Energy conservation and balancing in WSN

Extending the life of a wireless sensor network is critical to important applications such as battlefield surveillance where the nodes of the network must continue to be monitored and reported for a maximum period rather than getting exhausted in a less span of time, leading to interruptions in the network, division due to depletion of energy, etc. Due to the constraints exhibited by nodes of the WSN, it is necessary to utilize energy in an efficient way by introducing novel techniques and approaches to extend the lifetime of the WSN [25, 26]. In this section, the significance of the



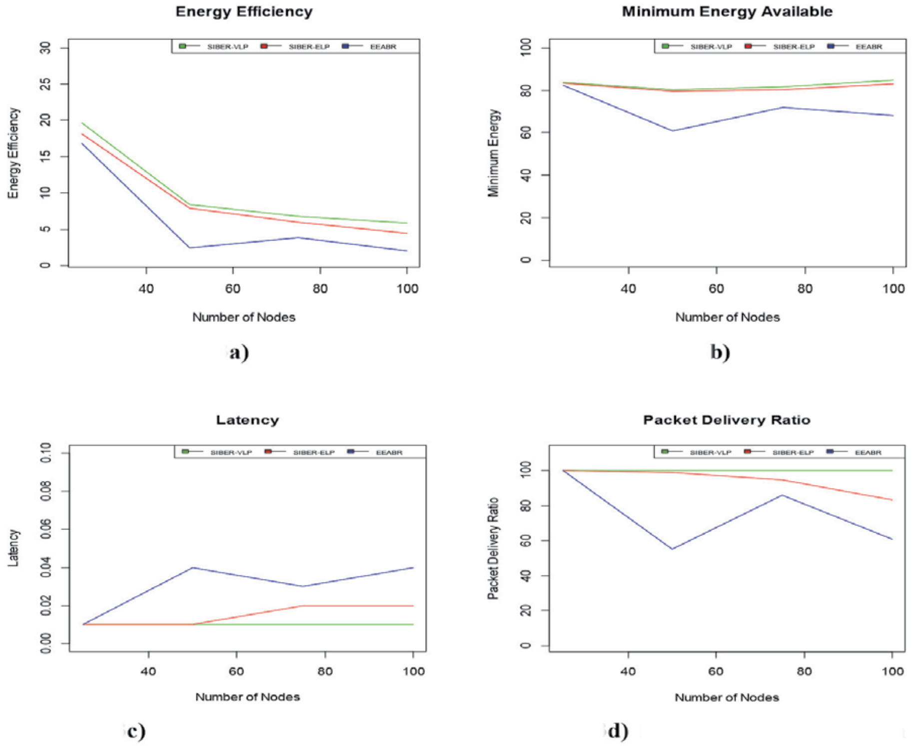
a) b) c) d)

Figure 2.
(a) Static EE evaluation. (b) Static ME evaluation. (c) Static LT evaluation. (d) Static PDR evaluation.

conservation of energy and its balancing using threshold energy concept (TECB) among nodes [27, 28] in SIBER-XLP is presented. The basic assumption taken here is that every node can participate in packet forwarding process if and only if it has sufficient energy larger than the threshold energy (E_{th}). Also, the least minimum threshold ($E_{th_{\min}}$) is introduced which is set to a minimum value. If any node's energy reaches $E_{th_{\min}}$, this bottom point disables the node in the packet forwarding process. E_{th} is a tunable parameter that means based on the traffic occurring on the network, E_{th} can be set to a value by which all the nodes get an opportunity to participate in the packet forwarding process by which the network life time will be extended. Initially, E_{th} is chosen a high percentage value of the node's total energy, so that every node involves in the routing. Once the energy of the node reaches the E_{th}, it can be reduced to a suitable value by which one of the neighboring nodes with good quality participate in forwarding packets or to a least minimum threshold ($E_{th_{\min}}$) at which point node is disabled to participate in forwarding packets.

In general, any application can be viewed with three different kinds of traffic—low level, medium level and high level. Eth can be set to these three levels in different scenarios. For low level traffic scenario, Eth can be raised to a high value, i.e. 70–80% of the energy, for the active nodes participating in the forwarding process with the intention that only little fraction of their energy can be utilized. Likewise, medium level traffic, E_{th} can be adjusted to a medium level value, i.e., 50% of the available energy, and then only 50% of the battery energy will be utilized. For high level traffic scenarios, a small value can be fixed for E_{th}, i.e. 20–30%, as a result nodes participating in packet forwarding process will have more energy available for utilization.

The role of E_{th} is to limit the amount of power from the nodes that will be provided for use in accordance with the capabilities in a heterogeneous network.



a) b) c) d)

Figure 3.
(a) Dynamic EE evaluation. (b) Dynamic ME evaluation. (c) Dynamic LT evaluation. (d) Dynamic PDR evaluation.

This would help to maintain the capacity of the less proficient nodes by involving them only when needed. In addition, nodes with higher capacity are involved in routing until its capacity reaches E_{th}. One may not generally have balanced paths to reach the sink with a nearly identical hop count or latency in a multipath routing. Because of the preference given to smaller distance paths with nodes having high power, the shorter paths will be chosen normally, as a result a fast decrease in the node's power in the path selected caused by the improper energy or load balance. Here, E_{th} parameter helps neighboring nodes to non-participate in forwarding packets if node's energy becomes equal/or less than E_{th}. This E_{th} control attribute conserves energy in the nodes for nearly future purpose and allows less leading nodes in the neighborhood to involve in the routing process until their levels of capacity attain E_{th}, hence conservation and balancing of energy is achieved among the neighbor nodes all the time. NS-2 Simulator is used to find the performance of the network under varying load or traffic. Based on the load, it is decided to adjust the E_{th} value of the nodes in order to conserve and balance energy by involving all the nodes alternatively in data forwarding process. In this simulation, three different kinds of traffic – low level, medium level and high level are considered. E_{th} can be set to these three levels in different scenarios. For low level traffic scenario, E_{th} can be raised to a high value (20 J) as initial energy is set to 30 J, i.e. 70% of the energy, for the active nodes participating in the forwarding process with the intention that only little fraction of their energy can be utilized. Likewise, medium level traffic, E_{th} can be adjusted to a medium level value, i.e., 50% of the available energy (15 J), and then only 50% of the battery energy will be utilized. For high level traffic scenarios, a small value can be fixed for E_{th} (10 J), i.e. 30% of the initial energy, as a

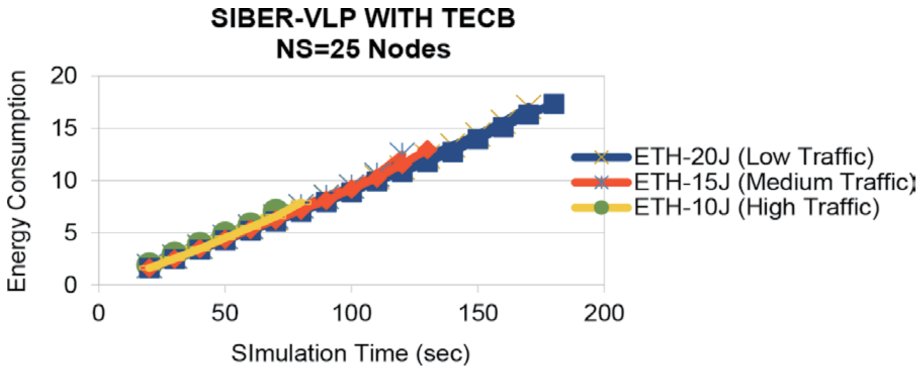


Figure 4.
Siber-VLP with TECB.

result nodes participating in packet forwarding process will have more energy available for utilization. In this simulation, the network performance, i.e. energy consumption is computed and how long the network is alive is seen based on the Eth value for different types of applications based on the traffic or load. Energy consumption graphs in **Figure 4** show that with the increase in simulation time, energy consumption increases which is not beyond E_{th} and number of nodes involved in forwarding the packet also increases. It is clear from the graphs that the nodes balance energy along both shorter and longer paths by setting E_{th} to only a particular value such as 10 J of energy, 15 J of energy or 20 J of energy which is accessible at each node. Same amount of energy is available on all the participating nodes at the end of the simulation period. This results in balancing energy and conserving energy, thus prolonging the lifetime of the network. There is 66% of initial energy conservation in the network for E_{th} = 20 J. For E_{th} = 15 J, there is 50% and 33% for high traffic scenarios having E_{th} = 10 J. Energy decreases with the rise in time, but does not fall below threshold energy in each and every case.

4. SIBER-DELTA model

Prolonging the network lifetime with the introduction of Threshold Energy concept alone is not sufficient for WSN as seen in the SIBER-XLP Model because of their constraints such as limited battery energy, limited memory, security threats, etc. As all the nodes are involved in the packet forwarding process, there is a security threat occurring from the insider nodes. In mission critical applications like military, health or commercial applications, nodes play a vital role to carry and deliver very critical and secret data. But, when a node gets compromised and misroutes the data to a wrong destination, it leads to loss of information. Also, misbehavior of nodes in the network can cause performance degradation resulting in non-forwarding attacks. There will be reduction in the system throughput with these attacks as packets need to be retransmitted many times if they are not delivered. Denial of service attacks can increase the delay in delivering the packets because some nodes which are used as forwarders may be busy in replying to the attacks and forced to delay the processing of other packets. With such attacks, network can be partitioned and communication may not take place. Finally, misbehaving nodes could also affect resources of the network by making the resource unavailable for routing. Denial of Service attacks force the adversary nodes to consume more energy during packet reception and processing unnecessarily. To tackle these misbehaving nodes in the network, SIBER-DELTA (Swarm Intelligence Based Efficient Routing protocol for WSN with Distance, Energy, Link quality and Trust Awareness) is developed as an extension to

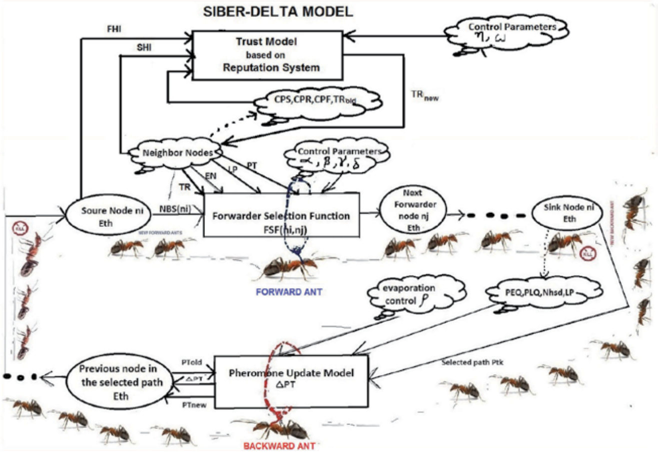


Figure 5.
SIBER-DELTA model.

SIBER-XLP to safeguard data exchange and secure data delivery. The concept of trust comes into picture in an open environment where the nodes are exposed to different types of attacks such as eavesdropping, non-forwarding attacks, denial of service attacks, etc. Hence, it is now essential to design a trust enabled routing model taking into consideration distance, energy and link quality. The proposed SIBER-DELTA Model [29] is shown in **Figure 5**.

SIBER-DELLTA Model has three components such as FSF, PUM and Trust Model (TM). The trust evaluation starts by an assumption that links in the network are bidirectional. Initially each node is associated with a trust value of 1 as no data transmission happens. As and when data forwarding takes place, there comes the trust model for evaluating a node's performance. There are two types of information obtained from the nodes of the network by the source node. One is the information received from its direct interaction with the neighbor whom it is sending data which is stated as First Hand Information (FHI). The other is the information received from the remaining neighbors of the source node except the direct neighbor which is stated as Second Hand Information (SHI). The source node calculates the Forwarding Misbehavior Index (FMI) of a node by recording all the information regarding data forwarded and data received. Mistrust Index is then calculated with the help of weighted average of FMI based on FHI and SHI. With these calculations, current trust rating of a node is depicted. Over a period of simulation time, a new current trust rating is also calculated based on their behavior in the past, so as to provide some incentives to the node for active participation or punishments to the node for misbehaving such as packet dropping. At last, final trust value of a node is calculated based on weighted average of the new current trust value and average of its trust rating in the past history. This allows handling of selective forwarding attacks in a smooth fashion. Instead of completely avoiding nodes in the routing process as done in the case of Black Hole attacks, the final trust calculation helps the selective forwarding nodes to improve their trust values based on their past history.

4.1 Trust evaluation

The nodes in the network are initially assigned a trust value of 1. Upon the data forwarding from one node to another node, trust values are altered. The information received from direct neighbors and indirect neighbors allows calculating Forwarding Misbehavior Index of each neighbor node.

Forwarding Misbehavior Index (FMI) based on Direct Interaction (FHI) is given by:

$$DIFMI(n_i, n_j) = \frac{CPR(n_i, n_j) - CPF(n_j, n_i, n_k)}{CPS(n_i, n_j)} \tag{11}$$

where n_i is source node, n_j is the direct neighbor and n_k is the next neighbor of n_j.

FMI based on Indirect Interaction (SHI) is given by:

$$IDFMI(n_i, n_j) = \frac{\sum_{n_k \in NBS(n_i)} FMI(n_k, n_j) * TR(n_k)}{|NBS(n_i)| - 1} \tag{12}$$

Mistrust Index (MI) is a weighted average calculation of both FMI based on FHI and SHI. Based on value of the weighted coefficient used, importance will be given to either FHI or SHI. For equal importance of FHI and SHI, the weighted coefficient must be assigned 0.5, as it lies between 0 and 1.

$$MI(n_j, n_i) = \eta * DIFMI(n_i, n_j) + (1 - \eta) IDFMI(n_i, n_j) \tag{13}$$

Current Trust Rating (CTR) of a node n_j upon n_i is calculated by just subtracting the mistrust value from 1.

$$TR(n_j, n_i)^{curr} = 1 - MI(n_j, n_i) \tag{14}$$

New Trust Rating based on previous Trust Rating (NTR) is a weighted average calculation of the previous trust rating of a node n_j in the previous update interval and the Current Trust Rating of a node n_j.

$$TR(n_j, ni) = \omega * TR(n_j, n_i)^{curr} + (1 - \omega) * TR(n_j, n_i)^{old} \tag{15}$$

This is calculated because, upon the time consumption, there may be changes taking place in the node behavior. So as to provide some incentives to the node for active participation or punishments to the node for misbehaving such as packet dropping, this NTR is framed.

Final Trust Rating based on Past History (FTR) of a node is calculated based on weighted average of the New Current Trust Rating value and Average Trust Rating of node n_j (ATR) in the past history, by which selective forwarding attacks can be handled.

$$TR_{avg}^{m}(n_j) = \frac{\sum_{ph=k-m}^{k-1} TR(n_j, ph)}{m} \tag{16}$$

$$TR(n_{j,} n_i) = \omega * TR(n_{j,} n_i)^{curr} + (1 - \omega) * TR_{avg}^{m}(n_j) \tag{17}$$

Instead of completely avoiding nodes in the routing process, as of Black Hole attacks, the Final Trust Calculation helps the selective forwarding nodes to improve their trust values based on their past history.

Forwarder Selection Function is similar to the previously described Forwarder Selection Function in the SIBER-XLP model but with an additional trust parameter included.

$$FSF(n_i,n_j) = \left\{ \begin{array}{l} \dfrac{[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}[TR(n_i,n_j)]^{\delta}}{\sum_{j\in NBS(n_i)}[PT(n_i,n_j)]^{\alpha}[EN(n_j)]^{\beta}[LP(n_i,n_j)]^{\gamma}[TR(n_i,n_j)]^{\delta}}, if j \in NBS(n_i), \\ 0, otherwise, \end{array} \right\} \tag{18}$$

The Pheromone Update Function is also similar to the previously described Pheromone Update Function in the SIBER-XLP model but with an additional Path Trust Rating parameter included.

$$\Delta PT = PathEnergyQuality * PathLinkQuality * PathTrustRating$$

$$\Delta PT = \left(\frac{E_{avg}}{E_{in}} - \left(1 - \frac{E_{\min}}{E_{avg}}\right)\right) * \frac{LP(Pt_k)}{Nh_{sd}(Pt_k)} * \frac{\sum_{n_k\in NS(Pt_k)} TR(n_k)}{|NS(Pt_k)|} \tag{19}$$

4.2 Performance evaluation

Our proposed system, SIBER-DELTA was simulated using open source NS-2 simulator. In this simulation, we have considered static and dynamic network scenarios with random topology with nodes randomly distributed. Random way-point mobility model is used for dynamic network with the nodes having the ability to move with a specified speed.

Our proposed trust enabled routing approach SIBER-DELTA is compared with SIBER-VLP [24] without trust awareness for varying network sizes (dimension)—50 and 100 nodes by introducing 10, 20, and 30% non-forwarding attackers in the network. It is assumed that all the methods use the same data rate. The performance evaluation metrics used in this simulation are Packet Delivery Ratio, Latency, Dropped packets, Average Energy Consumed, Average Energy Remaining, Minimum Energy, Energy Efficiency(Kb/J), and Standard Deviation. In our model, all nodes are assigned initially equal trust rating during the initialization and setup phase. The Performance of the network with 50 nodes and 100 nodes in both static and dynamic scenarios are shown in **Figures 6** and 7, respectively. It is clearly seen from the simulation results that SIBER-DELTA model with trust implementation exhibits high packet delivery ratio. By avoiding completely untrusted nodes and considering only trusted nodes (i.e., nodes with higher trust rating) along the paths from source to sink, SIBER-DELTA is able to achieve a high success rate of 99.51%

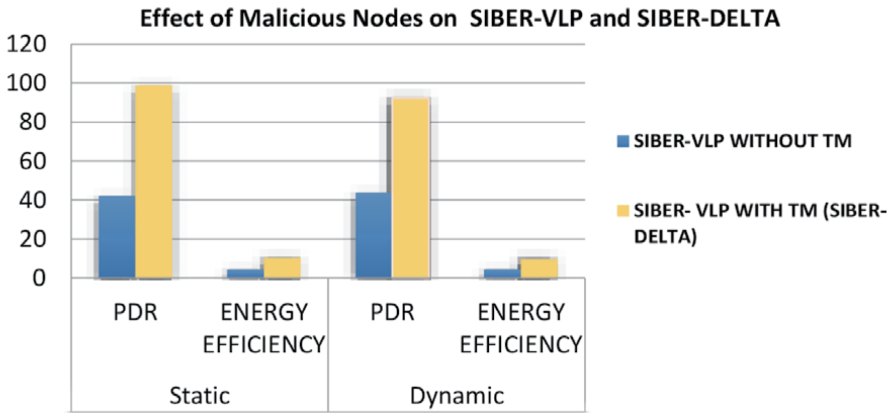


Figure 6.
Performance of the network (NS = 50 nodes).

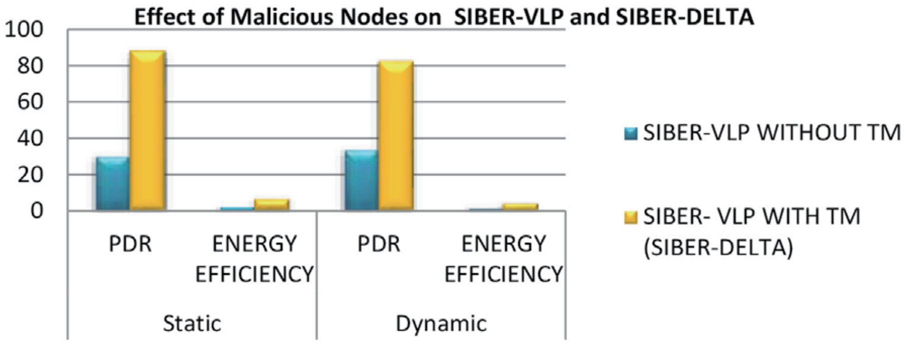


Figure 7.
Performance of the network (NS = 100 nodes).

with 10% attackers, 98.88% with 20% attackers and 98.35% with 30% attackers in the network. Since very less number of packet drops are observed during the entire simulation, it can be concluded that SIBER-DELTA performs extremely well by detecting all malicious nodes along the paths from source to sink and preventing these untrusted nodes from packet forwarding completely to achieve higher observed success rate. As evident from simulation results, SIBER-DELTA shows higher Energy Efficiency in the case of 10 and 20% attackers and slightly lower Energy Efficiency for 30% attackers as it consumes slightly higher energy due to the selection of longer alternate paths with more nodes to avoid black holes.

5. SIBER-DELTAKE model

SIBER-DELTAKE [30] Hybrid Routing protocol for WSN, an extension to trust aware routing model SIBER-DELTA is presented in this section which uses K-medoids clustering technique integrated with ECC to enhance security while selection of cluster head. This prevents the intruders from tampering the confidential information traversed across the network. This enables the early detection and termination of malicious nodes, based on the computation of values. WSN in IoT era is highly susceptible to security attacks due to huge data generation in modern era. To achieve better security, ECC is used in conjunction with authentication, key generation, group management, random number generation and key distribution techniques there by strengthening the existing security options. This will also result in better energy utilization when considering big data environment [31]. The system flow diagram of the proposed model is shown in **Figure 8**. In this approach, k-medoid clustering algorithm is chosen to select the cluster head and other members of the cluster family based on the calculation of distance between the midpoint and the sink node of the cluster. Once this is done, SIBER-DELTA mechanism is applied to update the FSF and PUM of a node. Finally, a node is permitted to transmit data based on its trust value. If the trust value of a node ready to transmit is high, then before transmission of data, it is encrypted using ECC algorithm. At the other end, if the trust value is obtained low, then the node under consideration is discarded, being regarded as a malicious node. The proposed model deals with identification of attacks and performs the following simplified steps—Initialization Phase involving network deployment, Clustering Phase using K-Medoids Algorithm, Routing Phase using SIBER-DELTA Protocol and Packet Forwarding Phase using Elliptic Curve Cryptography Technique.

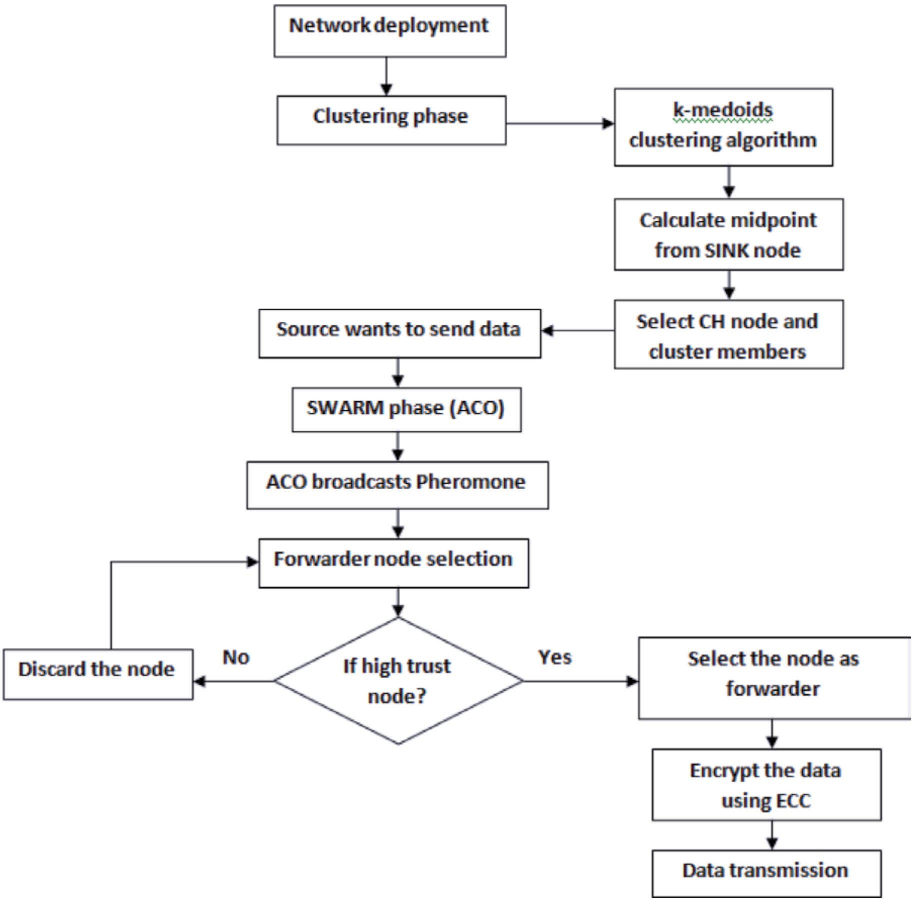


Figure 8.
SIBER DELTAKE system model.

5.1 K-Medoids algorithm (KM)

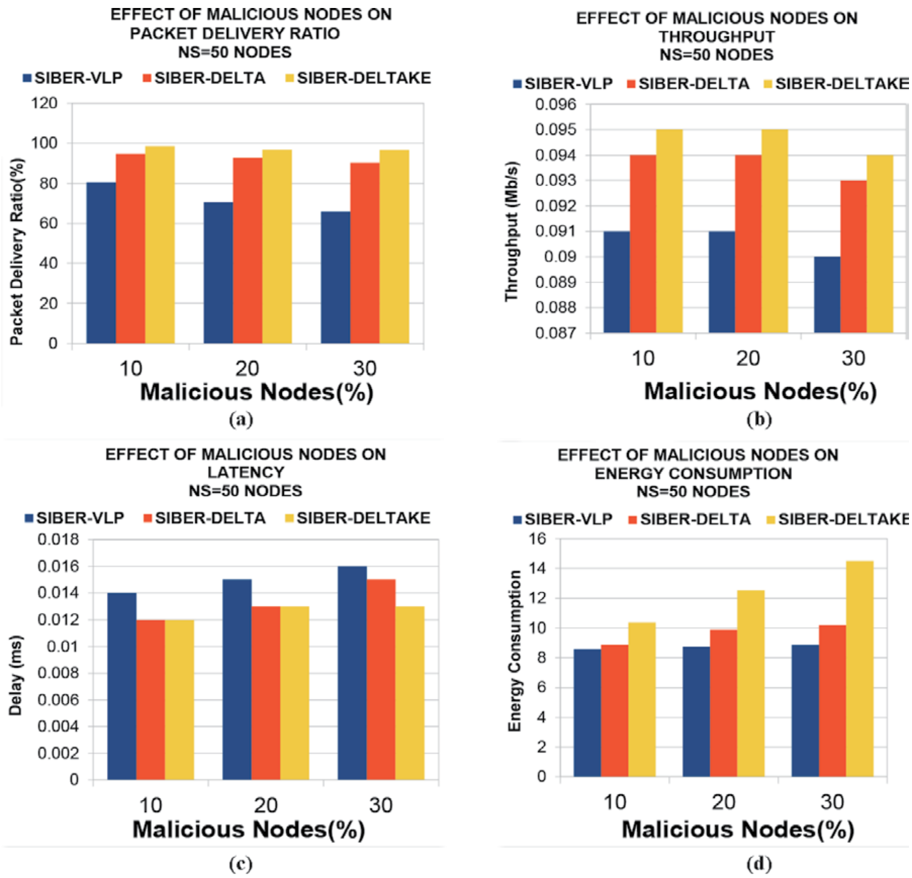
Our model SIBER-DELTAKE uses K-medoids algorithm for the formation of clusters and selection of cluster heads. *K*-medoids clustering [32] is a variant *to K*-means approach which is more robust to noises and outlier that are commonly recorded in the data generated in modern world, particularly sensor data. *K*-medoids approach uses an actual point in the cluster to represent the center of a cluster instead of using the mean point. The object, medoids with the minimum sum of distances to other points is most centrally located. The K-medoids algorithm is a partitioned clustering algorithm or segregating around medoids where data points are chosen to be the medoids. The object of a cluster which is known as mediod, where the average dissimilarity to all the objects in the cluster, is minimal. The representative objects K is first computed by this algorithm are called as K-medoids. Each data set object is assigned to the nearby medoid after finding the set of medoids. The various steps used in the K-Medoids algorithm are as follows: Step 1: Select k random points as the medoids initially from the given data set of n data points. Step 2: Each data point is associated with the closest medoid using the most common distance metrics. Step 3: Calculate the total swapping cost$TC_{ih}$for each pair of selected object i and non-selected object h. Step 4: Replace selected object i by object h if $TC_{ih} < 0$. Step 5: Repeat the steps 1 to 4 until there is no change in the medoids.

5.2 Elliptic curve cryptography(ECC)

The most desired approach in WSN to implement public key cryptography is ECC which is based on the algebraic structure of elliptic curves over limited fields [33]. An elliptic curve over prime field Fp, where p is a large prime number, is defined by a cubic equation of the form $y^2 = x^3 + ax + b$ where $a, b \in Fp$ are integers that satisfy the equation $4a^3 + 27b^2 \neq 0$. To have ECC based secure communication, every sensor node in the network must know an elliptic curve in addition to base point p which lies on the curve. It is assumed here that during the initial setup or the initialization phase, the elliptic curve parameters and also the base point p are loaded before only into the memory of every sensor node. Every node chooses a random prime integer as its private key and generates its public key by multiplying the private key by the base point p in order to have a secure communication between a pair of nodes. As cluster heads are involved in receiving the encrypted data from their members of cluster, then processing the data to perform data aggregation and finally forwarding the aggregated data to the base station, they consume more energy when compared to the member nodes. In order to reduce the energy consumption by cluster heads, cluster heads combine the encrypted message arriving from the members of the cluster and use Homomorphic encryption to perform aggregation of the encrypted data with no decryption thereby reducing the energy consumption of cluster heads. This results in saving of more energy and much stronger privacy of data as attackers will not be capable to hack data from intermediary nodes.

5.3 Performance evaluation

Our proposed hybrid model SIBER-DELTAKE was simulated using NS-2 simulator by considering static network scenarios with network sizes of 25, 50 and 100 nodes randomly distributed in the network area of 1000x500 m^2. Our proposed SACO-KM-ECC based SIBER-DELTAKE system is compared with SIBER-DELTA [28] with trust awareness and SIBER-VLP [22] without trust awareness for varying network sizes by introducing 10, 20, and 30% attackers in the network. The performance of the network is evaluated using the following metrics—Packet Delivery Ratio, End to End Delay, Energy Consumption and Throughput. It is evident from the plots in **Figure 9(a)** that SIBER-DELTAKE and SIBER-DELTA models exhibit high packet delivery ratio and SIBER-DELTAKE performing better than SIBER-DELTA as more trusted and secure optimal paths are selected to forward the packets resulting in higher performance. As it is seen from simulation results, SIBER-VLP model exhibits performance degradation as malicious nodes are introduced in the network. As the number of malicious nodes increase, an increase in packet drops is observed due to the presence of more malicious nodes in the paths selected by the ants. It can be seen from **Figure 9(d)** that SIBER-DELTAKE consume little more energy when compared to SIBER-VLP and SIBER–DELTA but it is reasonable considering the fact that hybrid model needs to perform ECC computation to provide data confidentiality and data Integrity in the presence of trust awareness. Though packet delivery ratio is less in SIBER-VLP, but the comparable energy consumption in this case may be due to both packet routing and packet retransmissions. As far as the end to end delay is considered, it can be seen from **Figure 9(c)** that hybrid model has low delay when compared to other models as it selects always the most trusted and secure optimal paths. Moreover, as the number of nodes increases, there will be more number of alternate paths available to route the packets so that the malicious nodes along the selected paths can be avoided. It is clear from the **Figure 9(b)** that SIBER-DELTAKE has higher throughput when



(a) (b) (c) (d)

Figure 9.
(a) Effect of malicious nodes on PDR-50 nodes. (b) Effect of malicious nodes on TP-50 nodes. (c) Effect of malicious nodes on LT– 50 nodes. (d) Effect of malicious nodes on EC-50 nodes.

compared to SIBER-DELTA and SIBER-VLP. SIBER-VLP performs very poorly in the existence of larger malicious or faulty nodes in the network.

6. Conclusion and future work

In this chapter, swarm intelligence and social insects based approaches are presented to deal with bio-inspired networking framework. The proposed approaches are designed to tackle the challenges and issues in the WSN field such as large scale networking, dynamic nature, resource constraints and the need for infrastructure-less and autonomous operation having the capabilities of self-organization and survivability. This research work presents the necessity to consider a combination of evaluation parameters for efficient routing of packets from source to destination with the development of SIBER-XLP with TECB, SIBER-DELTA and SIBER-DELTAKE models, each one emerging as an improved extension over the other. NS2 simulation environment was used to develop the entire work. The outcomes achieved in terms of results can serve as a contribution to the research community in the area of WSN with further levels of security to be integrated in future due to the voluminous data generation in modern world with the development of IOT applications. Also, in this work, a set of parameters like packet delivery ratio, latency, throughput, energy consumption, minimum available energy are evaluated against a collection of nodes. In future, a different set of parameters like load balancing across the nodes in a cluster, multi-level security aspects in WSN can be developed.

Another interesting and fascinating research direction is the application of Blockchain technology in WSN area. The blockchain technology enables peer to peer transfer of digital assets without any intermediaries and was originally created to support the famous cryptocurrency, Bitcoin. With the rapid development of Ethereum platform in recent years, the blockchain has permeated a broad range of applications across many industries and poised to innovate and transform a wide range of applications including finance, healthcare, government, manufacturing and distribution namely supply chain, digital media transfer, remote service delivery, platform for decentralized business, distributed resources, identity management, etc. The blockchain infrastructure establishes a trust among the peers in a decentralized system by having a process in place to validate, verify, and confirm transactions, record the transactions in a distributed ledger of blocks, create a tamper-proof record of blocks, chain of blocks, and implement a consensus protocol for agreement on the block to be added to the chain. Thus, validation, verification, consensus, and immutable recording lead to the trust and security of the blockchain. Though the application of block chain technology to WSN is in its initial stages, there has been research reported lately in the literature [34, 35] of using blockchain technology in peer authentication and trust level management for decentralized sensor networks. The blockchain infrastructure has shown tremendous advantages in a distributed decentralized network, but due to the limited computational power, battery life, bandwidth and more importantly storage, it may not be realistic to include all the blockchain features. In order to adopt a blockchain in WSN, we need to closely examine the operations involved in the blockchain implementation. For every transaction, a block is to be created, stored, source/sink node and transaction are to be validated & verified, broadcasted in a peer to peer network environment for block update. The role of the miners is most important to determine a valid block to be added to the blockchain using a consensus protocol based on a simplified Proof-Of-Work or Proof-Of-Stake (need to avoid biased or selfish nodes colluding to stake claim) approach which calls for having high capacity, powerful nodes to act as miners in WSN. Considering the challenges and issues with respect to the use of blockchain technology, another important network model decision would be the deployment of hierarchical sensor network with efficient clustering approach. Hence, there is a stronger need to design and develop efficient frame work and techniques to tackle the huge challenges and issues faced by blockchain technology in Wireless Sensor Network as WSN has emerged as the core component of IOT area.

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Chapter 9

Energy Saving Hierarchical Routing Protocol in WSN

C. Parvathi and Suresha Talanki

Abstract

The area of Wireless Sensor Networks (WSN) bring a new era of connected on-demand embedding systems which are mostly resource constrained. Despite of having design and operational challenges in real-time, WSN is currently being deployed for wide range of applications where traditional networking systems are most of time unfeasible. The prime focus of the study is to realize the significance of energy efficient routing in WSN. The core motivation is derived by addressing energy problems of WSN. An extensive analysis drawn from reviewing literatures, clearly shows that very few studies incorporated optimization towards modeling the routing schema. This chapter introduces a methodology consisting of three different types of analytical modeling where two of them focus on energy efficient clustering and another one is integrated to attain higher degree of security during data aggregation. The chapter basically provides an insight into the background of the problem which is related with the energy and security in WSN and also further provides preliminary information regarding the research overview. Further the study performs a thorough investigation on existing literatures to extract the open research problem. It basically highlights the gap which still exists and does not meet the requirements of proper energy and security demands. Literature survey on hierarchical protocols of WSN and their basic characteristics towards energy conservation is performed.

Keywords: energy, hierarchical, QoS, routing protocol, WSN (wireless sensor network)

1. Introduction

1.1 Preamble

In the era of Wireless Sensor network-(WSN), an energy-aware mechanism especially routing protocols, are the major concerns in the research area. This chapter presents a brief discussion about the major power consumption factors that causes the node to run out of their energy due to which WSN becomes non-functional. In addition, this chapter also discusses various existing hierarchical routing mechanisms introduced for energy saving goal in WSN.

Factors Associated to Energy Consumption in WSN This section demonstrates the fundamental characteristics and necessary aspects of WSN in order to understand the cause, factor, and requirements for designing energy saving routing mechanism. The literature review is the research method used in this chapter which is a more relevant method than ever.

1.2 Background of WSN

Before discussing about the energy consumption related factors, it is essential to explain about the background of WSN. The concept of WSN is not new, and since the last 10 decades, it has got lots of popularity among the researchers. However, WSN has the vast potential of sensor network to facilitate real-time and automated services with very less human interaction property. The deployment of WSNs, have attracted various working field of real-time applications such as in (i) Military application: for target localization and for tracking war event, (ii) Medical application: for healthcare monitoring and real-time medical data sharing for diagnosing, (iii) Industrial applications: for monitoring robotic system, the security system, and surveillance system, (iv) Environmental application: for monitoring the environmental factor and events, like this there are many more internal and external application where the concept of WSN are used. There are different technical issues for different applications that the researchers are still working for developing an efficient solution [1, 2].

These technical issues arise due to the constraint nature of WSN that includes many limited properties such as, low-cost and limited battery-operated sensors nodes, limited connectivity & coverage range and less processing and limited transmission capacity. The Routing mechanisms in WSNs are responsible for constructing the paths among the targeted nodes and also to perform multihop communication between nodes in a network for which WSN requires an effective and feasible technique to perform energy efficient routing operation for reliable communication, transmission & data processing [3].

- Energy Utilization: Energy utilization in WSN is defined as a total difference between the initial power and the final power. The following is the numerical expression that can be used to define energy-utilization mathematically:

$$\begin{aligned} \tau \text{ consumption} &= \eta \\ \tau \text{ consumption} &= \sigma + \gamma + \mu \\ \pounds \text{ utilization} &= \tau \text{ consumption-}\tau \text{ consumption} \end{aligned} \tag{1}$$

The above Eq. (1) illustrates the mathematical definition of $\pounds$ utilization-(energy-consumption) where ι consumption is the initial energy depletion factor, and τ consumption is the total energy depletion factor. The ι consumption is calculated using η (residual energy before performing any operation), and τ consumption is calculated using the addition of total energy consumed in operation of σ (sensing), γ (data forwarding & receiving) and μ (data processing).

2. Analysis of power depletion by sensor nodes

In WSN a single sensor node consists of four components: fixed limited battery, a sensing module, wireless module and data processing module. The energy consumed in data processing and sensing operation is quite low whereas the maximum energy is absorbed in the communication layer of the wireless module.

In the wireless communication operation, the sensor node responsible for data forwarding and data receiving which takes very high energy for communication process in the sensor nodes deployed in the network. **Figure 1** displays the energy consumption ratio with various sensors states [4, 5].

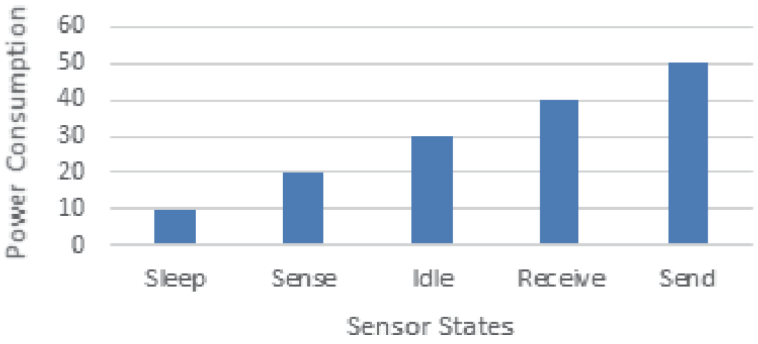

Figure 1.
Power consumption by sensor node in different states.

3. Energy consumption issues

The energy utilization issue in WSNs is a fundamental problem which is directly associated to its lifetime. Therefore, it becomes the primary goal to be solved while designing WSN architecture. In WSN, the energy supplied to the sensor is usually battery-powered, and the sensor cannot reach to the level of long-term operation without recharging [6]. Also, sensors are typically used in remote or harsh environments, such as battlefields, where it is not possible to charge or replace the battery from all sensor's nodes. Furthermore, sensor network lifetime having a strong dependency on the other intermediate nodes because, as failure of some intermediate sensor nodes lead to significant topology changes and that require re-routing process for communication and data-packets transmission in the network. The following are the main factors that cause complexities while designing energy efficient mechanism in WSN [7]:

- Limited availability of power in the sensor node
- Dynamic topology
- Data collection process
- Data redundancy
- Intermediate node malfunctioning
- Long Coverage
- Packet overhead
- Environmental factor

The following are some steps which have been introduced by several researchers and practitioners for improving WSN lifecycle

- Setting unwanted sensors into sleep mode
- Modifying transmission range so that the sensor node can transmit the data using efficient energy to their neighbor nodes

- Deployment of sensors in a hierarchical network so that cluster heads can be used to aggregate data and reduce the amount of information sent up to the sink

- Efficient Routing optimization mechanism

- Hierarchical Routing strategy, so that data is sent along the shortest path to the target node using the least number of nodes and will conserve energy

3.1 Data exchange and communication process in WSN

This section discusses the process of node communication for data exchange in WSN.

The node communication process in WSN uses radio frequencies as a wireless medium to link themselves among other sensors and follows a routing strategy for performing data exchange communication process in the network. Therefore, routing operations conducts a process of path retrieval where the message is communicated from the source node to the destination node. From the viewpoint of existing research studies, it has been observed that the routing protocol is the primary focus for improving energy consumption and other performance parameters in WSN. However, designing an effective routing protocol is very challenging under the constraints and dynamic topology of the WSN [7, 8].

- **Challenging Task** – Designing an energy efficient mechanism for extending WSN lifetime without compromising network reliability and other QoS parameters.

- **Routing** Protocols **in WSN.**

In WSN, routing protocols are designed on various processes based on the network structure, routing operation, path organization, etc. **Figure 2** demonstrates the routing process based on different formulation strategies [9, 10].

The above **Figure 2** also shows the fundamental consideration for designing routing protocols in WSN to select the appropriate path to exchange data and communicate between the source node and the destination node.

- The routing protocol based on the Path organization includes:

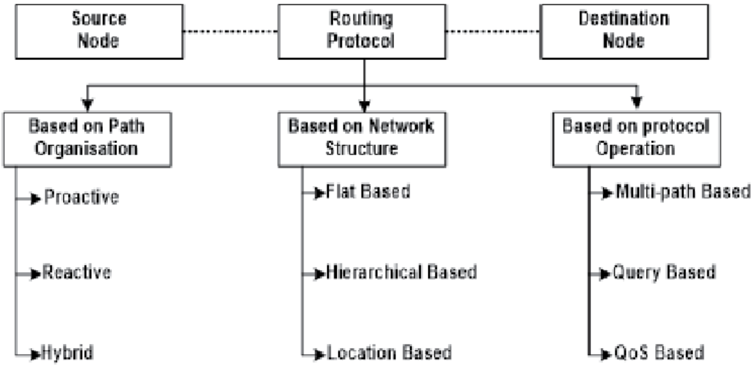

Figure 2.
Fundamental formulation strategies for routing process in WSN.

   i. **Proactive routing approach:** In this, the protocols have to maintain a routing information table before initiating the path discovery phase and this is also known as table-driven routing approach.

   ii. **Reactive routing approach:** In this protocol, the initialization of the path discovery process for data exchange is based on the requirement of route demand.

   iii. **Hybrid routing approach:** In this, both reactive and proactive routing is used in the combined form.

- **The routing protocol based on the protocol operation includes:**

   i. **Multi-path-based routing approach:** Multi-path protocol for routing operation is an alternate process in which protocol selects multi-path to deliver data from source to destination. This is mainly designed to overcome the limitation of single route data transmission in order to achieve more reliability and load balancing.

   ii. **Query-based routing approach:** Here, the target node broadcasts a query message between the nodes. After receiving the query message, the node replies to the target node with a query matching message. After matching the query from both side nodes, then it initiates a data exchange process between them.

   iii. **QoS based routing approach:** In this protocol, the routing is selected on the basis of QoS parameters such that the network must ensure the efficient load balance between energy consumption and data quality (bandwidth, delay, reliability, etc.)

- **The routing protocol based on the Network Structure includes:**

   i. **Flat based routing approach:** In this routing approach each node has a similar role in which sharing of data packets is performed through several intermediate nodes.

   ii. **Hierarchical based routing approach:** In this approach, routing is performed in an efficient way to utilize low energy as much as possible to increase the lifetime of WSN. In this, the nodes with higher energy are prioritized to form a cluster that are responsible for data forwarding and processing, whereas the nodes with lower energy are selected as a normal node to sense events and collect raw data.

   iii. **Location-based routing approach:** In this approach, routes are initialized based on the estimation of sensor location. Also, in order to preserve node energy, some nodes are switched into sleep mode when no events and activities are found at the location of such nodes.

The above Sections 1 and 2, briefly introduced the background of WSN and its fundamental problem (energy consumption) and further introduced the routing process involved in WSN. The proposed system focuses on hierarchical routing protocols to make the WSN active longer. The next section presents an extensive analysis of the existing hierarchical routing protocol.

3.2 An extensive analysis of conventional hierarchal routing protocols

In WSN the nodes are deployed densely, and some of them are placed too tightly which cause data redundancy when transmitting collected data to the base station. Therefore, the hierarchal routing protocol uses a clustering approach in order to lower the energy consumption by avoiding redundancy factor in the data transmission process. The clustering mechanism involves a cluster of nodes and cluster head selected according to node residual energy to forward the aggregated data from the clusters without processing redundant data. The following are some of the existing hierarchical routing protocols discussed [11, 12]:

3.2.1 LEACH – (low energy adaptive clustering hierarchy)

LEACH is introduced as the first hierarchical routing protocol that uses TDMA (Time Division Multiple Access) to implement the energy efficient routing process in the WSN. The LEACH protocol enables a clustering mechanism that forms a set of nodes based on received signal strength. This set of nodes is also referred to as a cluster, where each node of the clusters is devoted towards the extra opportunistic node called as Cluster-Head (CH). The CH acts as a local data center for all the clusters and uses TDMA and CDMA scheduling to transmit aggregated data to the base station (BS) without intra-frame and inter-frame cluster collisions [13–15].

- A salient characteristic of LEACH
    - Clustering based Protocol
    - Self-orienting cluster configuration
    - Adaptive and randomized cluster configuration
    - Localized controls for cluster organization and data transfer operations
    - Low-power data access
    - Data aggregation
    - Local compression to minimize overall communication

The operation involved in LEACH protocol is segregated into rounds where each round contains two phases to perform cluster-formation, CH formation, and data transmission in power efficient way.

The following are the two phases which is involved in the LEACH operation.

- Setup Phase
- Steady Phase

i. Setup Phase

This is the initial phase of the LEACH protocol, in this phase, a grouping of nodes and CHs are formed. The nodes are organized themselves into different groups and these groups with its member nodes is termed as clusters. Initially, each node in the cluster chooses itself to become a CH with a certain probability, and as a

CH node, it must contain higher energy than a non-CH node. In the LEACH protocol, the CH selection mechanism is constructed in such a way that CH can randomly change over time to balance the energy dissipation of the nodes and thereby cluster nodes gets an opportunity to become CH in next cycle.

- Formation of CH- The nodes in the cluster uses a random function to choose a number between 0 and 1. If the number found to be less than subsequent threshold value $\nu(\mathrm{x})$, then the node becomes the CH of the current cycle.

$$\upsilon(x) = \left\{ \begin{array}{r} \theta/1 - \theta * (r \bmod 1/\theta) : fx \in Y \\ 0 : \boldsymbol{Otherwise} \end{array} \right\} \tag{2}$$

The above Eq. (2) demonstrates the computation of threshold value, where r is the number of cycle that has completed, x indicates the overall nodes in the network, θ indicates the percentage of the CH, and Y is the non-CH node. Here in this, each node can generate a random number between 0 and 1 and the node becomes CH when its number is found to be less than $\nu(x)$, otherwise it will not become CH. Once the CH is selected using the Eq. (2), the CHs-node uses a non-aggressive Carrier-Sense-Multiple-Access (CSMA)-transmission protocol to broadcast the notification message to inform all the other nodes which have played a role for selecting CH in the current cycle. Now based on received signal strength (RSS) of the broadcast notification message, all the non-CH nodes identify that which cluster it belongs to. After each node verified to which cluster it belongs to, then the nodes must have notified to CH that it is a member of its cluster. Therefore the CH plays a role of local data-center to control the transmission of the data packets in its cluster. The CH then initiates TDMA to construct the schedule, then forwards this schedule to all nodes presented in the cluster to ensure that there are no conflicts between data and message transmissions. In order to save power, it also allows each node to put their radio components in a sleep mode outside of their data transmission job. Therefore, the setup phase is complete when all nodes in the cluster are aware of the TDMA schedule, and the steady phase begins.

ii. Steady-State Phase

In this phase, the data transmission operation is executed in different frames. In this frame, the cluster node forwards its data to the CH node according to its transmission schedule. In order to preserve energy, each cluster node uses less power dissipation mechanism based on the RSS value of the CH broadcast notification message. Afterward, the CH receives all data from the cluster nodes and then performs the data aggregation operation and transmits resultant data to the sink node (**Figure 3**).

- Analysis of energy consumption in LEACH

The LEACH protocol considers that cluster nodes start with the same energy and the likelihood function with threshold value v(x) not recognizes the remaining power of each node. Therefore, the LEACH gets good reduction rate in energy utilization comparing to direct communication process and MTE routing protocols. However, LEACH distributes the similar-level power-loads to all nodes of clusters, and this will further result in an imbalance of node after running for a long time. Also, if a node with less energy is selected as the CH, the node may quickly drain its energy. If this happens then, the CH will terminate and lose their connectivity to all nodes belonging to its cluster.

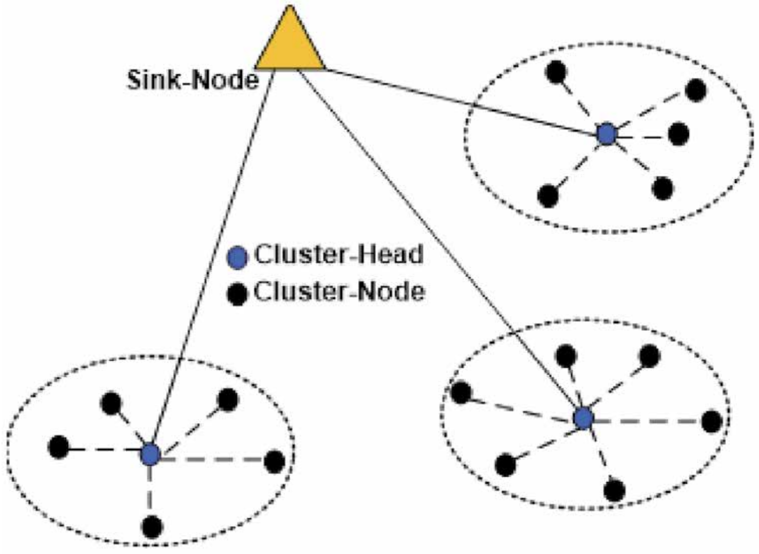

Figure 3.
Clustering mechanisms in LEACH protocol.

- Advantages of LEACH Protocols

    i. LEACH protocol uses a clustering mechanism which enables less communication load between sensors and Sink.

    ii. The CH performs data aggregation which leads to minimizing the redundancy factor and saves energy.

    iii. In this CH uses a scheduling process that allows member nodes to enter into sleep mode. This avoids collision factor and preserves the extra energy consumption.

    iv. LEACH protocol also allows each sensor node in the cluster to become the CH.

    v. Random rotation of CH also enhances network lifetime.

    vi. It also saves energy by following a single hop routing process from the sensor to CH.

    vii. LEACH does not require the location of the nodes to establish as CH.

    viii. LEACH is independent and distributed which does not require control information from the sink node.

    ix. LEACH protocol has one of the big disadvantages is this that if anyhow CH dies then the cluster nodes will become useless their collected data will not reach to the sink node.

- **Radio Energy Model**

This section presents a simple concept of Energy radio model, used by the hierarchal routing protocol such as LEACH, PEGASIS, etc. [16, 17].

The following are the assumptions for Radio Energy Model (REM)

- The REM considers sensor nodes and Sink are all stationary and Sink node is deployed outside from the sensing field.
- It also considers that all nodes are aware of their location.
- All sensor nodes are considered as homogeneous that have the same energy supply.

Figure 4 displays the first order radio model that considers most of the energy is consumed in the communication operation performed by the sensor nodes. Therefore, it demonstrates that the energy needed to forward kbits-packets is computed by Eq. (3) and energy utilized in packet reception can be computed by Eq. (4).

The LEACH protocol uses radio energy model for power dissipation in the communication process. The numerical Eqs. (3) and (4) is demonstrated below to compute energy utilization in transmission and energy utilized in the receiving process.

$$E_T(\kappa, \partial) = \begin{cases} \kappa E_{power} + \kappa \varepsilon_{fs} \partial^2, \partial < \partial_0 \\ \kappa E_{power} + \kappa \varepsilon_{amp} \partial^4, \partial < \partial_0 \end{cases} \tag{3}$$

$$E_R(\kappa) = \kappa E_{power} \tag{4}$$

The above Eqs. (3) and (4) illustrates the energy dissipation rate in the communication process of sensor nodes. The ETx(k,∂) is the transmission energy needed for (kbits-packets) over ∂ distance and Epower is the electric power utilized per bit to run the communication module such as transmission circuit and receiver circuit based on modulation and digital coding. fx∂2 and amp∂4 is the amplification power which is based on the significant rate of bit-error. The ∂0 is the square root of dividing power utilization in data aggregation by fx∂2 and amp∂4.

3.2.2 PEGASIS – (power-efficient gathering in sensor information systems)

PEGASIS is introduced as an enhanced version of the hierarchical routing protocol over the LEACH. The PEGASIS protocol follows a chain-based approach where all sensor nodes formulate a chain system, and one leader node is selected randomly to execute data transmission process to sink node. In this, the collected

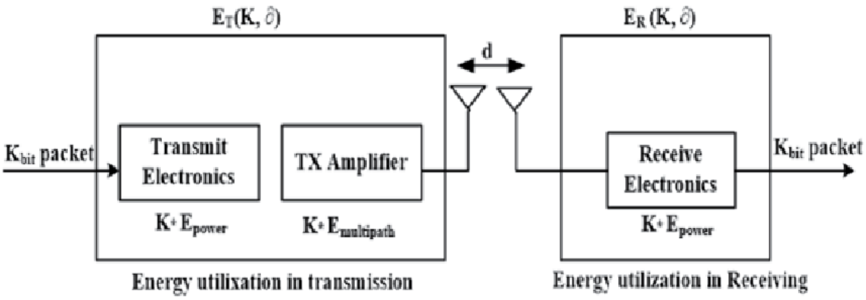

Figure 4.
Energy radio model.

data transfers via a node to node and if any node fails between the chain process, then the node rearranges themselves to bypass the deadly node and reconstruct chain to continue their process. The primary goal of PEGASIS is to receive and transmit data from the nearest neighbor and forward it to sink node with the support of leader node. The PEGASIS protocol involves two phases to achieve chain process which is mentioned as follows [18, 19]:

- Chain formulation
- Data Gathering

i. **Chain Formulation:** The chain structure proceeds in a greedy manner, i.e. from starting nodes to the last node at the sink node and nearest node of the just previous node is selected as a next node, and in the same way all nodes will continue to arrange themselves in this pattern until a suitable chain is formed. Furthermore, the node in the chain is only able to place itself at one location. In each round, a leader node is selected randomly. In the construction phase, the protocol uses a greedy algorithm with considering that all sensor nodes are globally aware of the network condition and sensor location. When the sensor node fails due to power loss, the chain is rebuilt by utilizing the greedy method and by omitting the failure sensor nodes.

ii. **Data Gathering:** The concept of PEGASIS protocol avoids the formation of clusters and CH. It considers that, only a single node as a leader-node instead of multiple nodes in the chain to transmit collected data to the sink node. In this, raw data is collected and carried from one node to another node, then it is aggregated and finally leader node forwards to the sink node.

The above **Figure 5** demonstrates the chain formation and data collection and transmission process. The nodes N1, N2, N3, N4, and N5 have arranged themselves in a chain structure where N3 is randomly chosen as leader node and remaining are the normal participating nodes. The N1 forward its data to N2 then after N2 aggregates the collected data and transmits it to N3. Now, N3 broadcasts token message to N5. The node N5 sends its data to N4 then N4 aggregates collected data and transmits it to N3. The node N3 as leader node collects data from its both neighbor and then it fuses, and aggregates collected data itself and transmits to sink node (SN).

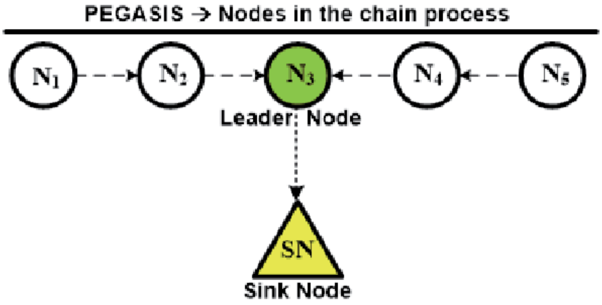

Figure 5.
Chain formation and data processing.

- Advantages of PEGASIS
    1. It uses a greedy mechanism to build chain of nodes that result in a low overhead communication process.
    2. In this, communication process is not disturbed because when any node fails, the protocol reconstructs the chain and is allowed to continue the data collection and transmission process.
    3. Only leader node has permission to send data directly to the sink node.
    4. It decreases energy consumption in communication operation and prolongs the network lifecycle.
- Disadvantages of PEGASIS
    1. PEGASIS considers that each sensor nodes in chain carry an equal level of energy.
    2. This protocol sometimes results in delay because it takes more time to collect data from the distance node in the chain.
    3. In this, the single leader-node can also act as a bottleneck for the other nodes.
    4. Each node in this protocol needs to be aware of network information.

3.2.3 TEEN – (threshold sensitive energy efficient sensor network protocol)

TEEN is a hierarchical clustering protocol that binds sensor nodes and forms a cluster of nodes where each node of the cluster is operated by CH. In this CH collects data from their member node and then forwards it to their higher CH node, the CH aggregates the data and delivers to the sink node. In this scenario, at each cluster varies with the time where the CH broadcast threshold value to its member nodes [20, 21].

- Hard threshold: In this threshold value is broadcasted for the sensed attribute where the role of sensor nodes is to sense and report back its data to their associated CH.
- Soft threshold: In this, a small modification is made in the sensed attributes where it triggers the node to switch transmitter to on mode.
- Later, the sensed attribute value is stored in the internal node memory. Then based on the following condition the sensor node forwards its data in the current cluster round.

i. The value of the current sensed attribute must be higher than the hard threshold value.

$$S_{current} > H_{cuttoff} \quad (Condition\ 1)$$

ii. The value of the current sensed attribute must vary from the stored sensed value, and its difference value should be equal or greater to the soft threshold value.

$$(S_{current} \neq S_{stored}) \geq S_{cuttoff} \quad (Condition\ 2)$$

Whenever these conditions are met, the hard-cutoff attempts to minimize the burden of transmissions by permitting the sensor nodes to forward data only when the sensed attribute exists in the area of interest.

The above **Figure 6** demonstrates, the time line operation of TEEN protocol where it represents a little variation in the sensed attributes value and allow to sensor nodes to become active form sleep mode in order to forward the data to CH. Therefore, if the value of the sensed attribute does not change or changes minimally, the soft cutoff value will reduce the transmission load of the sensed data. Based on the hard-cutoff value, the node will only transmit the sensed data according to end user requirement and resulting in more energy preservation through making changes relative to earlier data report. When the next cycle initiates, the CH is to be changed, then a new value of parameters broadcasts.

TEEN is very practical for the user interactive applications where a user can dynamically control energy efficiency and perform trade-offs between the data accuracy, reliability and its response time. In this, Clustering formation process uses a layered approach as well as data-centric approach. The key feature of this protocol is that it is ideal for the real-time operated applications. Therefore, TEEN is best considered to be used in the reactive network because it saves power consumption during communication and data transmission. Also a critical drawback of this protocol is that if the threshold is not reached, then user will not be able to obtain any data packets.

- Cluster formation in TEEN

In this protocol, CH basically follows the concept of LEACH. In TEEN, first a cluster is formed; afterwards CH is selected by its member nodes. The CH broadcasts two threshold values to all of its member nodes. This process will continue for each cluster change time. The clustering and data collection process in TEEN is shown in **Figure 7**, where clusters are formed in a hierarchical arrangement, with CH and cluster nodes and data shared to the sink nodes through higher-position CHs.

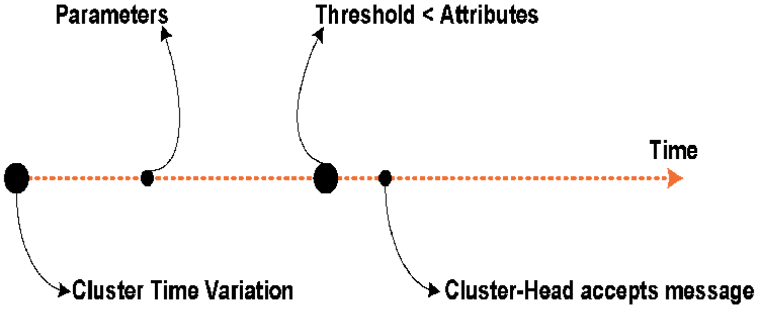

Figure 6.
Operation of TEEN protocol.

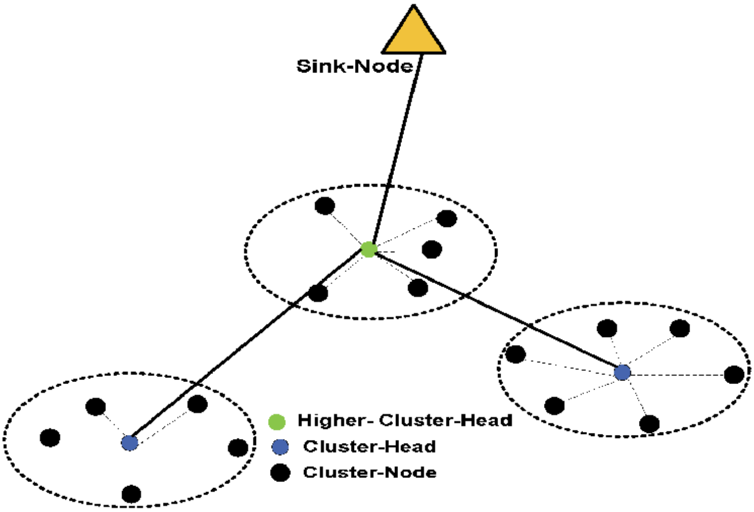

Figure 7.
Clustering process in TEEN.

- **Advantages of TEEN Protocol**
    1. This protocol is most suitable for the time-dependent applications.
    2. It allows users to dynamically control response times, intrusion identification, and explosion detection, and also allows performing a tradeoff between energy efficiency and data accuracy.
    3. It also saves the energy through hierarchical clustering mechanism.
- **Disadvantages of TEEN Protocol**
    1. For vdata transmission, process, nodes may have to wait for their time slots allotment.
    2. If the node has no data to transmit, the time slot assigned to the node may be useless.
    3. The cluster head always looks for data that causing its receiver transmitter continuously open.

3.2.4 APTEEN – (adaptive threshold sensitive energy efficient sensor network protocol)

APTEEN was introduced as an improved version of TEEN to enhance the performance of the TEEN protocol to support the regular data collection process. The architecture of APTEEN is similar to the architecture of TEEN. APTEEN also follows a hierarchical clustering approach to achieve energy efficient communication between source sensors and receivers (SINK nodes). An enhanced feature of this protocol is that it allows the node to periodically transmit its sensed data, and if any rapid variations are found in the sensed attributes, then the sensor accordingly respond its report to CH. In this version, CH is also responsible for performing data aggregation operations to reduce power consumption in data processing tasks. Once

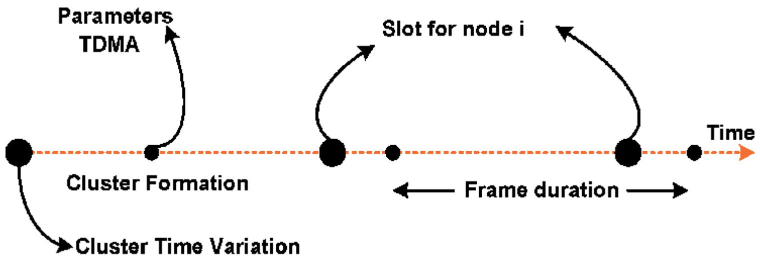

Figure 8.
Operation of APTEEN.

Sink node decides the cluster, the following are the parameters that are broadcasted by the CH (**Figure 8**):

i. Attributes: In this user are curious to get all data related to physical parameters.

ii. Threshold -value: In this there are two threshold value i.e. Hard threshold and soft threshold value which is as same as used in TEEN protocol.

iii. Schedule: In this, TDMA is used to assign a time slot to every sensor node.

iv. Count Time (TC): It is the maximum duration among two consecutive reports forwarded by the sensor nodes.

The node continuously observes its surroundings, whose sense value is higher than the hard threshold value. Once the node senses a value that exceeds the threshold value, then it only sends the data when the value of the sensed attribute changes to the total quantity equal to or greater than the defined soft threshold value. If the node fails to send data for the duration set equal to the count time, then the system asks to recollect and resend the data. TDMA is used to set up scheduling in which each node in the cluster is assigned a transmission slot.

- **Advantages of APTEEN**

  i. It provides feature of both proactive network and reactive network.

  ii. Proving periodic data to user, it demonstrates clear picture of the whole network.

  iii. Highly responsive to any reaction on its attributes.

  iv. It provides, flexible and scalable feature to the user, so that user can perform modification, set time intervals and attribute threshold values.

  v. It allows to control power consumption factor by regulating time count and the threshold values.

- **Disadvantages of APTEEN**

  i. In this cluster formation takes place in multi-level, that sometime results in overhead.

ii. The second disadvantage is that it requires additional complexity to threshold-function and time count.

3.2.5 HEED – (hybrid, energy-efficient distributed clustering protocol)

HEED Protocol is introduced as an extension of LEACH feature in order to acquire power balancing feature for cluster selection by utilizing residual energy and node density. It works in multi-hop pattern within inter-cluster communication through adaptive power transmission. The HEED protocol is mainly introduced for achieving following features:

i. Extends network life-span by allocating energy consumption.

ii. The clustering process ends within a constant number of iterations.

iii. Lowering the overhead problem.

iv. Provide a homogeneous distribution of CH and a solid pattern of clusters.

In this protocol the cluster formation processes perform in various cycles. Each cycle takes long duration to get messages from corresponded nodes in the cluster. A probability factor is used to bound the initialization of CH selection at first cycle. In this, every sensor node uses a probability factor to become a CH. The mathematical expression is given as follows:

$$N_{CH-prob} = C_{prob}\left(\frac{P_{Rresidual}}{P_{\max}}\right) \tag{5}$$

The above Eq. (5), NCHprob is the probability of node that wants to be becomes CH, Rresidual is the estimated remaining energy in the senor node and Pmax is the maximum power equivalent to a charged battery source.

In this the Value of NCHprob must be higher than the minimum threshold value Tmin. If NCHprob < 1, then CH is an temporary-CH or if its NCHprob equal to 1, then NCH will become is the final CH. The recent elected CHs will be added to the current CHs set. If the sensor node is elected to be CH, then it broadcasts the message as it becomes temporary CH or a final CH. The node that hearing the CH lists chooses the CH with the minimal cost from the group of CHs. Afterwards, each nodes increase its probability value to become CH in next round. If the sensor node completes cycle of HEED execution without choosing to become a CH or to connect to the cluster, it will declare itself to be the final CH. If a temporary CH node hears from a lower cost CH, it can become a regular node in a later iteration (**Table 1**).

- **Advantage of HEED protocols**

i. This protocol enhances the life of network, thereby stabilizing adjacent nodes.

ii. It does not require any information about the network such as location.

iii. It also does consider the distribution of nodes.

	Leach	**Pegasis**	**Teen**	**Apteen**	**Heed**
Classification	**Hierarchical**	**Hierarchical**	**Hierarchical**	**Hierarchical**	**Hierarchical**
Proactive	Yes	Yes	Yes	Yes	Yes
Energy Conservation	Very Good	Very Good	Good	Good	Yes
Network life time	Good	Very Good	Very Good	better	Good
Data Based	No	Yes	Yes	Yes	Yes
Data Aggregation	Yes	Yes	Yes	Yes	Yes
Location Based	No	No	No	No	No
Qos-Supported	No	No	No	No	No
Multipath	No	No	No	No	No
Optimal Path	No	No	No	No	No
Robustness	better	better	better	better	Better
Scalability	Good	Good	Good	Good	Good
Security	No	No	No	No	No

Table 1.
Comparison Conventional Hierarchal Routing Protocols [22].

iv. In this protocol the sensor nodes node updates its neighbor timely forwarding and receiving messages in the multi-hop network.

v. In HEED the Nodes only need their neighborhood information to built a cluster

- **Disadvantage of HEED Protocols**

i. In this protocol the CH are selected in random patterns that may cause communication overhead problem that leads to exhaust extra energy and affects other QoS parameters.

ii. In addition, another factor affecting network lifetime is the periodic rotation of the CH during the selection process, which results in the exhaustion of additional energy to rebuild the cluster.

4. Summary

This chapter briefly discusses the various power-aware existing hierarchical routing protocols designed for WSN. Initially, this chapter discussed the background of the WSN and the factors associated with energy utilization in sensor nodes. The common goal of all of the above discussed protocols is to extend the life of the WSN by minimizing energy consumption without affecting packet transmission. It is also emphasized that all protocols have some limitations and advantages. The main motivation for this chapter is to analyze the difficulty and issues in existing routing protocol in order to design an effective low-power consumption routing protocol.

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Chapter 10

Research on Polling Control System in Wireless Sensor Networks

Zhijun Yang and Lei Mao

Abstract

To solve the problem of multi-priority and multi-business tasks in wireless sensor networks, a two-level polling control system is proposed based on the basic polling system. The system divides the sites into ordinary sites and high-priority site according to business priorities. The ordinary sites use gated services, and the high-priority sites use exhaustive services. The mathematical model of the system is established by using the method of Markov chain and probability generating function, and the important parameters such as query period, throughput, average queue length and average delay are obtained. The simulation results are approximately equal to the theoretical calculation results, which shows that the theoretical analysis method is correct and effective. While distinguishing priority services, the system ensures the delay of users and improves the quality of service of the polling system.

Keywords: WSN, polling system, average queue length, average waiting delay, priority control

1. Introduction

With the rapid development of science and technology, human beings have been in the information age, and sensor technology, as the most important and basic technology of information acquisition, has also been greatly developed. Wireless sensor networks (WSNs) are a new generation of sensor network and the core of Internet of things technology [1]. It is an interdisciplinary research field involving sensor technology, computer network technology, wireless transmission technology, embedded computing technology, distributed information processing technology, microelectronic manufacturing technology, software programming technology and so on [2]. Through a variety of information sensors, it collects all kinds of needed information in real time, and realizes the functions of monitoring and management through the access of the Internet. In this process, the mode of data transmission must be considered. MAC protocol specifies the way that nodes occupy wireless channels when transmitting data. It reduces transmission delay and improves network throughput and service quality through communication protocol and mechanism. Therefore, the performance of MAC protocol determines the data transmission capability of WSNs [3].

MAC protocol based on polling access is a non-competitive control method, which allocates fixed channel resources to users [4]. In the process of data communication, the users who get the transmission right exclusively enjoy the allocated channel resources, so that the network can realize the conflict-free transmission of information. Due to its unique conflict-free transmission mode, polling-based MAC protocol has always been a hot topic in WSNs research [5, 6]. With the development of research, its service mode has been continuously expanded [7–9]. Kunikawa and Yomo proposed a polling MAC protocol based on EH-WSN, which improves the throughput of WSNs nodes [10]. Adan and his collaborators proposed a dual-queue polling model, and then analyzed the equilibrium distribution of the system by using the compensation method and a reduction to a boundary value problem respectively [11]. Abidini et al. studied the vacation queuing model and the single-server multi-queue polling model [12]. The polling system is mainly divided into three categories: gated, exhaustive and limited according to the service strategy [13]. Researchers have been studying all kinds of polling systems focusing on the optimization and improvement of system performance [14]. With the rapid development of modern network technology, a single service strategy has been unable to meet the needs, such as priority business and multi-business tasks. Therefore, it is necessary to make comprehensive use of various service strategies, but at this time the difficulty of system analysis is greatly increased. Yang and Ding analyzed the polling system with mixed service, but did not give an accurate analysis of the second-order characteristics of the system [15].

Herein, we first analyze the three basic polling systems, and then propose a two-level polling system model with exhaustive service in the central site and gated service in the ordinary sites, which not only solves the problem of differentiated priority business, but also ensures the delay of the system. Then the E(x) characteristics of the system such as average queue length, average query cycle and throughput are analyzed. Finally, the performance of the system is verified by simulation experiments.

2. Three basic polling system models

The basic model of the polling system consists of a logical server (relay site) and N sites. The server queries each site to provide services according to the predetermined service rules. The performance of the polling system is usually determined by the order of querying each site, the service policy of the site and the service order of information packets within the site. The system model is shown in **Figure 1**. When the system is running, the polling order is as follows: at t_n time, the server provides services for site i; after the service is completed, the server provides services for site $i + 1$ at t_{n+1} time.

2.1 Exhaustive service polling system

The exhaustive service system is when the server starts to serve the site, it not only transmits the previously arrived information packets in the site, but also transmits the newly arrived information packets during the service period. Its probability generating function at t_n time is:

$$\begin{aligned} G_{i+1}(z_1, z_2, \cdots, z_i, \cdots, z_N) &= \lim_{t\to\infty} E\left[\prod_{j=1}^{N} z_j^{\xi_j(n+1)}\right] \\ &= R\left[\prod_{j=1}^{N} A(z_j)\right] G_i\left(z_1, z_2, \cdots, z_{i-1}, B\left(\prod_{j=1\neq i}^{N} A(z_j) F\left(\prod_{j=1\neq i}^{N} A(z_j)\right)\right), z_{i+1}, \cdots, z_N\right) \end{aligned} \tag{1}$$

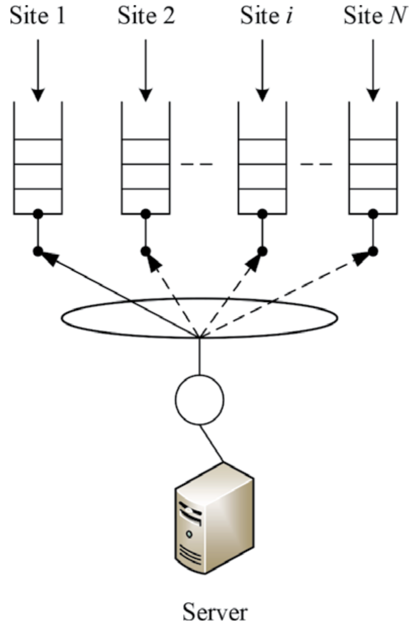

Figure 1.
Single-level polling system model.

where $F(z_i) = A(B(z_i F(z_i))); i = 1, 2, \cdots, N$ represents the probability generating function of the random variable of the time required for the server to provide exhaustive service to the information packets entering any site in any time slot.

2.1.1 Average queue length

The average queue length of the system is defined as the average number of packets stored in the site j when the ordinary i starts to receive service at t_n time, expressed by $g_i(j)$. Definition:

$$g_i(j) = \lim_{z_1, z_2, \cdots, z_i, \cdots, z_{N \to 1}} \frac{\partial G_i(z_1, z_2, \cdots, z_i, \cdots, z_N)}{\partial z_j} \tag{2}$$

According to the Eqs. (1) and (2), it can be calculated that the average queue length of information packets at site i is:

$$g_i(i) = \frac{N\gamma\lambda(1-\rho)}{1-N\rho} \tag{3}$$

2.1.2 Average waiting delay

The average waiting time of the system is the time it takes for a packet to enter the site until it is sent out, expressed by $E[w]$. Define the joint moment of random variable (x_j, x_k) as $g_i(j, k)$.

$$g_i(j,k) = \lim_{z_1, z_2, \cdots, z_j, \cdots, z_k, \cdots, z_{N \to 1}} \frac{\partial^2 G_i(z_1, z_2, \cdots, z_j, \cdots, z_k, \cdots, z_N)}{\partial z_j \partial z_k} i, j, k = 1, 2, \cdots, N \tag{4}$$

According to Eqs. (1) and (4), the average waiting delay of packets in the exhaustive-service polling system is calculated as follows:

$$E[w] = \frac{1}{2}\left\{\frac{R''(1)}{\gamma} + \frac{1}{1-N\rho}[(N-1)\gamma + (N-1)\rho + N\lambda B''(1)] + \frac{\rho A''(1)}{\lambda^2(1-N\rho)}\right\} \quad (5)$$

2.2 Gated service polling system

The gated service polling system means that when the server queries the site, it only provides services for the packets that currently arrive at the site, and the packets arriving in the service process will not provide services until the next round of access of the server. The definitions of average queue length and average waiting delay of gated service polling system are similar to that of exhaustive service polling system, and its probability generating function at t_n time is:

$$\begin{aligned} G_{i+1}(z_1, z_2, \cdots, z_i, \cdots, z_N) &= \lim_{t\to\infty} E\left[\prod_{j=1}^{N} z_j^{\xi_j(n+1)}\right] \\ &= R\left[\prod_{j=1}^{N} A(z_j)\right] G_i\left(z_1, z_2, \cdots, z_{i-1}, B\left(\prod_{j=1}^{N} A(z_j)\right), z_{i+1}, \cdots, z_N\right) \end{aligned} \quad (6)$$

2.2.1 Average queue length

According to Eqs. (2) and (6), the average queue length of the gated service polling system is:

$$g_i(i) = \frac{N\lambda\gamma}{1-N\rho} \quad (7)$$

2.2.2 Average waiting delay

According to Eqs. (4) and (6), the average waiting delay of the gated service polling system is:

$$\begin{aligned} E[w] = \frac{1}{2}\left\{\frac{R''(1)}{\gamma} + \frac{1}{1-N\rho}\left[(N-1)\gamma + (N-1)\rho + 2N\gamma\rho + N\lambda B''(1)\right.\right. \\ \left.\left. + \frac{(1+\rho-N\rho)A''(1)}{\lambda^2}\right]\right\} \end{aligned} \quad (8)$$

2.3 Limited service polling system

In the polling system with limited service, it is assumed that there are N terminal stations in the system, and the N terminal stations are queried by a server in turn. The server only serves one packet when polling each terminal station, and the rest of the packets is queued with the newly arrived packets to be sent in the next cycle with the same service rules. The average queue length and average delay of the limited service polling system are also consistent with those of the exhaustive service polling system, and its probability generating function at t_n time is:

$$G_{i+1}(z_1,z_2,\cdots,z_i,\cdots,z_N)=\lim_{n\to\infty}E\left[\prod_{j=1}^{N}z_j^{\xi_j(n+1)}\right]$$
$$=R\left[\prod_{j=1}^{N}A_j(z_j)\right]\left[B_i\left[\prod_{j=1}^{N}A_j(z_j)\right]\frac{1}{z_i}[G_i(z_1,z_2,\cdots,z_i,\cdots,z_N)\right. \tag{9}$$
$$\left.-G_i(z_1,z_2,\cdots,z_{i-1},0,z_{i+1},\cdots,z_N)]+G_i(z_1,z_2,\cdots,z_{i-1},0,z_{i+1},\cdots,z_N)\right]$$

2.3.1 Average queue length

According to Eqs. (2) and (9), the average queue length of the limited service polling system is:

$$\begin{aligned}g_i(i)&=\frac{N}{2[1-N\lambda(\gamma+\beta)]}\{2\lambda\gamma(1-\lambda\gamma)+\frac{(N-1)\lambda^2\gamma(\rho-\gamma)}{1-N\rho}\\&+\left[1+\frac{\rho}{1-N\rho}\right]\gamma A''(1)+\frac{N\lambda^3\gamma B''(1)}{1-N\rho}+\lambda^2R''(1)\}\end{aligned}\tag{10}$$

2.3.2 Average waiting delay

According to Eqs. (2) and (9), the average waiting delay of the limited service polling system is:

$$\begin{aligned}E(w)&=\frac{R''(1)}{2\gamma}+1/\{2[1-N\lambda(\gamma+\beta)]\}[(N-1)\gamma+(N-1)\rho\\&+2N\gamma\rho+(N\lambda\gamma+\rho)A''(1)/\lambda^2+N\lambda B''(1)+N\lambda R''(1)]\end{aligned}\tag{11}$$

2.4 Performance comparison of three polling systems

The above analysis method of embedded Markov chain and probability generating function are used to obtain the accurate expressions of the average queue length and average waiting time of three different service strategies, i.e., exhaustive, gated and limited service polling systems. In this section, the performance characteristics of three different service strategy polling systems are compared by setting the working conditions and operating parameters of the system. The system meets the following conditions:

1. The parameters of each station obey the same distribution law, i.e., the distribution is symmetric.

2. Arrival time, query conversion time, and waiting time for service are all measured in time slots.

3. The number of packets arriving at any time slot at each station obeys the Poisson distribution.

4. The polling systems with three different service strategies all satisfy the steady-state condition $\sum_{i=1}^{N}\lambda_i\beta_i=N\lambda\beta\le 1$.

It can be seen from **Figures 2** and **3**, the performance indicators of the polling systems with three different service policies, i.e., the average queue length and the average waiting delay are different. The average queue length of the exhaustive service polling system is the smallest, the gated service polling system takes the second place, and the average queue length of the limited service polling system is the largest, and the average waiting delay also satisfies the same law. From the perspective of fairness, on the contrary, the fairness of the limited service polling system is the best, while that of the exhaustive service polling system is the worst. The polling systems with three different service strategies have their own characteristics and advantages. In the actual situation, the appropriate polling service strategy should be selected according to the scope of application and application conditions to meet different application needs. When the system requires high fairness, select the limited service strategy; when the system requires high real-time performance, choose the exhaustive service strategy; when the system requires both real-time and fairness, choose the gated service strategy.

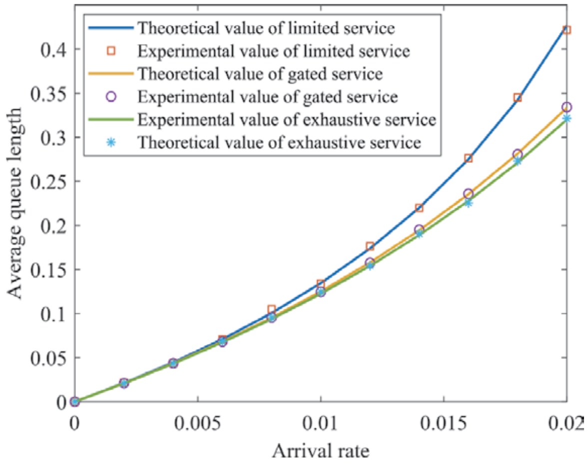

Figure 2.
Relationship between average queue length and arrival rate.

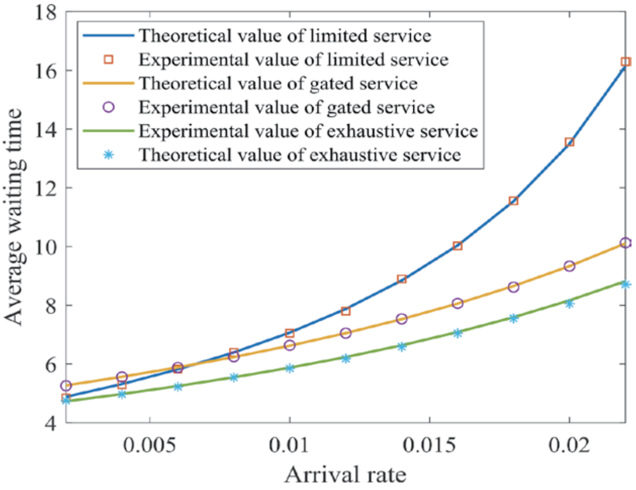

Figure 3.
Relationship between average waiting delay and arrival rate.

3. Exhaustive-gated two-level polling system

Based on the basic polling system and the requirements of different priority business in WSNs, an exhaustive-gated two-level polling access control strategy is proposed. The principle of the exhaustive-gated service two-level control polling system is as follows: the polling system is composed of N ordinary sites and a central site h. The server serves the central site according to the exhaustive service rule and the ordinary sites according to the gated service rule. The system model is shown in **Figure 4**. After the polling starts, the server first provides exhaustive service to the central site, i.e., the information arrived before the start of the service and the information arrived during the service until the site is empty, and then go to query the ordinary sites. If the ordinary site i is not empty, the server will serve it according to the gated service rule. When the service of the site i is finished, it will turn to query the central site h. After the central site completes the prescribed service, it starts to serve the ordinary site i + 1 again. The exhaustive-gated two-level control polling system distinguishes between the central site and the ordinary sites by always giving priority to the central site, and the service of the central site is guaranteed first.

We use the methods of stochastic process and probability generating function to analyze the performance of the system. The random variable $\xi_i(n)$ is defined as the number of information packets queued for service in the memory of the site i at the t_n time. $\xi_h(n)$ is the number of information packets queued for service in the memory of the central station at t_n time. The state variable of the whole system at t_n time is $\{\xi_1(n), \xi_2(n), \cdots, \xi_i(n), \cdots, \xi_N(n), \xi_h(n)\}$; at t_{n*} time, the state of the system is $\{\xi_1(n*), \xi_2(n*) \ldots \xi_N(n*), \xi_h(n*)\}$. At t_{n+1} time, the state of the whole system can be expressed as $\{\xi_1(n+1), \xi_2(n+1) \ldots \xi_N(n+1), \xi_h(n+1)\}$. Then the N + 1 states of the system constitute a Markov chain, which is aperiodic and ergodic.

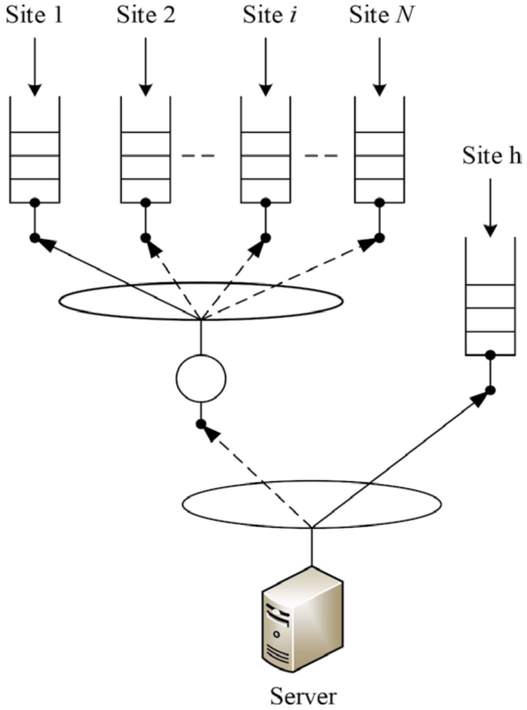

Figure 4.
Two-level polling system model.

3.1 Definition of variables

1. In any time slot, the process of information packets arriving at each station is subject to the independent and identically distributed Poisson process, and the probability generating function and mean value of its distribution in ordinary stations are $A_i(z_i)$ and $\lambda_i = A'(z_i)$ respectively. The probability generating function and mean value of the distribution of at the center site are $A_h(z)$ and $\lambda_h = A_h{}'(z)$ respectively.

2. The service time of an information packet of any site is subject to independent and identically distributed probability distribution. In the ordinary sites, the probability generating function, mean value and second-order origin moment of the distribution are $B_i(z_i)$, $\beta_i = B_i'(1)$ and $v_\beta = B_i''(1)$ respectively. The probability generating function, mean value and second order origin moment of the distribution at the center station are $B_h(z)$, $\beta_h = B_h{}'(1)$ and $v_h = B_h{}''(1)$ respectively.

3. After any ordinary station completes transmission service, the transfer time to the query center site is subject to an independent and identically distributed probability distribution, whose probability generating function, mean value and second-order origin moment are $R_i(z_i)$, $\gamma_i = R_i'(1)$ and $v_\gamma = R_i''(1)$ respectively. When the central site is converted to the ordinary site, the parallel control strategy is adopted, i.e., the server queries the next ordinary site that needs service while serving the central site, which saves the conversion time and improves the service efficiency of the system.

Define the following variables:
u_i: the time when the server moved from the ordinary site i to the central site.
v_i: the service time for the server to provide gated service to the ordinary site i.
v_h: the service time for the server to provide exhaustive service to the central site h.
$\mu_h(u_i)$: the number of information packets entering the central site within u_i time.
$\eta_h(v_i)$: the number of information packets entering the central site within v_i time.
$\mu_i(u_i)$: the number of information packets entering site i within u_i time.
$\mu_j(u_i)$: the number of information packets entering site j within u_i time.
$\eta_j(v_i)$: the number of information packets entering site j within v_i time.

According to the principle of the model, the state variables of the system at each time satisfy the following relations:

$$\begin{cases} \xi_j(n*) = \xi_j(n) + \mu_j(u_i) + \eta_j(v_i), j = 1, 2, \cdots, N, h; j \neq i \\ \xi_i(n*) = \mu_j(u_i) + \eta_i(v_i) \\ \xi_j(n+1) = \xi_j(n*) + \eta_j(v_h), j = 1, 2, \cdots, N, h \\ \xi_h(n+1) = 0 \end{cases} \tag{12}$$

3.2 Probability generating function

Assuming that the storage capacity of each ordinary site and the central site is large enough, the information packets will not be lost, and the information packets will be served in the order of first-come-first-served. The system reaches a steady state under the condition of $\sum_{i=1}^{N}\lambda_i\beta_i + \lambda_h\beta_h < 1$, and the probability generating function in the steady state is defined as:

$$\lim_{n\to\infty} P[\xi_i(n) = x_i; i = 1, 2, \ldots N, h] = \pi_i(x_1, x_2, \ldots x_i \ldots x_N, x_h) \tag{13}$$

$$G_i(z_1, z_2, \ldots, z_i, \ldots, z_N, z_h) = \sum_{x_1=0}^{\infty}\sum_{x_2=0}^{\infty} \cdots \sum_{x_i=0}^{\infty} \cdots \sum_{x_N=0}^{\infty}\sum_{x_h=0}^{\infty} [\pi_i(x_1, x_2, \ldots, x_i, \ldots, x_N, x_h) \cdot {z_1}^{x_1}{z_2}^{x_2} \ldots, {z_i}^{x_i} \ldots, {z_N}^{x_N}{z_h}^{x_h}] \tag{14}$$

According to Eqs. (12) and (14), when the two-level polling system provides services to the central site at t_{n*} time, the probability generating function of the system state variable is:

$$\begin{aligned} G_{ih}(z_1, z_2, \cdots, z_i, \cdots z_N, z_h) &= \lim_{t\to\infty} E\left[\prod_{i=1}^{N} z_i^{\xi_i(n^*)} z_h^{\xi_h(n^*)}\right] \\ &= R_i\left[\prod_{j=1}^{N} A_j(z_j)A_h(z_h)\right] \cdot G_i\left[z_1, z_2, \cdots, z_{i-1}, B_i\left(\prod_{j=1}^{N} A_j(z_j)\right), \cdots, z_n, z_h\right] \end{aligned} \tag{15}$$

The probability generating function of the system serving the ordinary site $i + 1$ at t_{n+1} time is as follows:

$$\begin{aligned} G_{i+1}(z_1, z_2, \cdots, z_N, z_h) &= \lim_{n\to\infty} E\left[\prod_{j=1}^{N} z_j^{\xi_j(n+1)} z_h^{\xi_h(n+1)}\right] \\ &= G_{ih}\left[z_1, z_2, \cdots, z_i, \cdots, z_N, B_h\left(\prod_{j=1}^{N} A_j(z_j) F\left(\prod_{j=1}^{N} A_j(z_j)\right)_i\right)\right] \end{aligned} \tag{16}$$

3.3 Average queue length

Definition: The average queue length $g_i(j)$ of the system is the average packets stored in node j when node i receives service at t_n time.

$$g_i(j) = \lim_{x_1, x_2, ..x_N, x_h \to 1} \frac{\partial G(z_1, z_2, \cdots z_N, z_h)}{\partial z_j} \tag{17}$$

The average queue length of ordinary stations calculated by Eqs. (15)–(17) is:

$$g_i(i) = \frac{\lambda_i \sum_{j=1}^{N} \gamma_j}{1 - \rho_h - \sum_{j=1}^{N} \rho_j} \tag{18}$$

The average queue length of the central station is:

$$g_{ih}(h) = \frac{\lambda_h \gamma_i (1 - \rho_h)}{1 - \rho_h - \sum_{j=1}^{N} \rho_j} \tag{19}$$

When $\lambda_1 = \lambda_2 = \cdots \lambda_i \cdots = \lambda_N$ $\beta_1 = \beta_2 = \cdots \beta_i \cdots = \beta_N$ $\gamma_1 = \gamma_2 = \cdots \gamma_i \cdots = \gamma_N$, the system is symmetrical and the average queue length of the ordinary site and the central site is respectively:

$$g_i(i) = \frac{N\lambda_i\gamma_i}{1 - \rho_h - N\rho_i} \tag{20}$$

$$g_{ih}(h) = \frac{\lambda_h\gamma_i(1 - \rho_h)}{1 - \rho_h - N\rho_i} \tag{21}$$

3.4 Average cycle

The average cycle of the polling system is expressed as the time interval between two consecutive visits to the same queue by the server, which is the statistical average of the time taken by the server to serve $N + 1$ sites according to the prescribed service rules. The calculation is as follows:

$$E[\theta] = \frac{\sum_{i=1}^{N}\gamma_i}{1 - \rho_h - \sum_{i=1}^{N}\rho_i} \tag{22}$$

3.5 Second-order characteristics

The joint moment of central site random variable (x_j, x_k) is defined as $g_{ih}(j,k)$, and the joint moment of ordinary site random variable (x_j, x_k) is defined as $g_i(j,k)$, which is obtained by the property of probability generating function.

$$g_i(j,k) = \lim_{z_1, z_2, \cdots z_N, z_h \to 1} \frac{\partial^2 G_i(z_1, z_2, \cdots z_i, \cdots z_N, z_h)}{\partial z_j \partial z_k} \tag{23}$$

It can be calculated from the Eqs. (15) and (23):

$$g_i(i,i) = \frac{\lambda_i^2}{\sum_{k=1}^{N}\rho_k(1+\rho_k)}\left[\sum_{k=1}^{N}\frac{\beta_k}{\lambda_k}(1+\rho_k)g_k(k,k) - \theta\sum_{k=1}^{N}\frac{\beta_k}{\lambda_k}(1+\rho_k)A_k''(1)\right] \tag{24}$$

$$g_{ih}(h,h) = \lambda_h^2 R_i''(i) + \gamma_i A_h''(1) + \left[2\lambda_h^2\beta_i\gamma_i + \lambda_h^2 B_i''(1) + \beta_i A_h''(1)\right]g_i(i,i) + \lambda_h^2\beta_i^2 g_i(i,i) \tag{25}$$

When the system is symmetrical:

$$\begin{aligned} g_i(i,i) = {} & \frac{N}{(1-\rho_h+\rho)(1-\rho_h-N\rho)}\{\lambda^2 R''(1) + \gamma A''(1) - \rho_h\gamma A''(1) \\ & + (N-1)\lambda^2\gamma^2 + \frac{1}{1-\rho_h-N\rho}[N(N+1)\lambda^2\rho\gamma^2 - \rho\rho_h\gamma A''(1) \\ & + N\lambda^3\gamma B''(1) + \rho\gamma A''(1) - (N-1)\lambda^2\rho\rho_h\gamma + (N-1)\lambda^2\rho\gamma \\ & + \lambda^2\beta_h^2\gamma A''_h(1) + \lambda^2\lambda_h\gamma B''_h(1) - 2\lambda^2\rho_h^2\gamma]\} \end{aligned} \tag{26}$$

3.6 Average waiting delay

Definition: The average delay of the polling system is the time it takes for an information packet to arrive at the site until the information packet is sent. According to the approximate expressions of $g_i(i,i)$ and $g_{ih}(h,h)$ calculated above, the average waiting delay can be obtained by substituting the following two expressions respectively.

The average waiting time for ordinary site is:

$$E(w_i) = \frac{(1+\rho_i)g_i(i,i)}{2\lambda_i g_i(i)} \tag{27}$$

The average waiting time at the central site is:

$$E(w_h) = \frac{g_{ih}(h,h)}{2\lambda_h g_{ih}(h)} - \frac{(1-2\rho_h)A_h''(1)}{2\lambda_h^2(1-\rho_h)} + \frac{\lambda_h B_h''(1)}{2(1-\rho_h)} \tag{28}$$

4. Experimental analysis

Based on the above two-level priority polling service model, theoretical value calculation and experimental simulation are carried out according to the following working conditions.

1. The data communication process is ideal and the data will not be lost.
2. The data entering each station in any time slot satisfies the Poisson distribution.
3. The polling system satisfies $\sum_{i=1}^{N}\lambda_i\beta_i + \lambda_h\beta_h = \sum_{i=1}^{N}\rho_i + \rho_h < 1$.

4.1 Symmetrical two-level polling system

Figures 5 and **6** show the change of average queue length and average waiting delay between the ordinary station and the central station with the arrival rate. It can be seen from the Figures that when the arrival rate is increasing, the average queue length and average waiting delay of information packets also increase. The queue length and delay of central station are much smaller than those of ordinary sites, which indicates that the model has strong ability to distinguish business.

Figures 7 and **8** show the comparison between the average queue length and the average waiting delay of the exhaustive-gated two-level polling system and the single-level gated polling system. It can be seen that in the case of the same network size, the queue length and delay of the two-level model are less than that of the

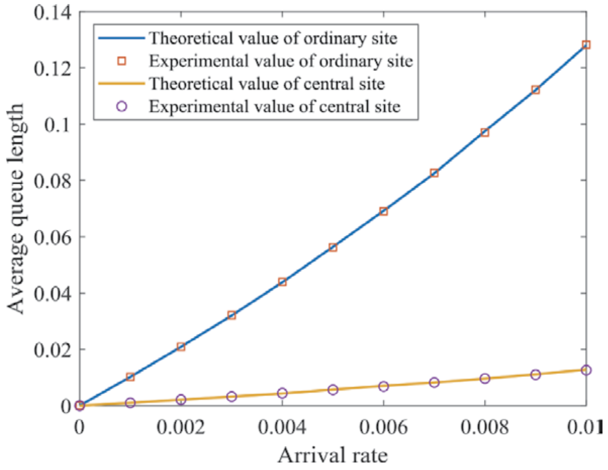

Figure 5.
Relationship between average queue length and arrival rate of symmetrical systems.

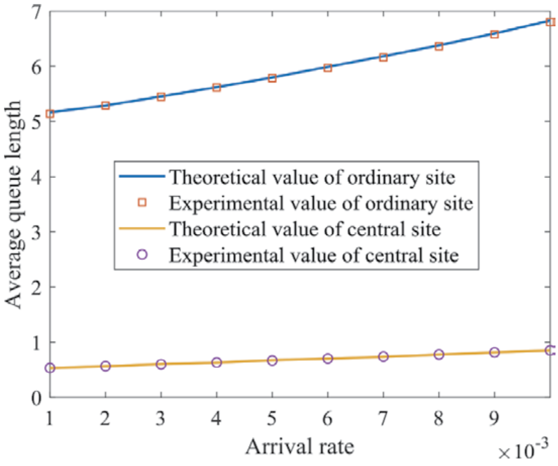

Figure 6.
Relationship between average waiting delay and arrival rate of symmetric systems.

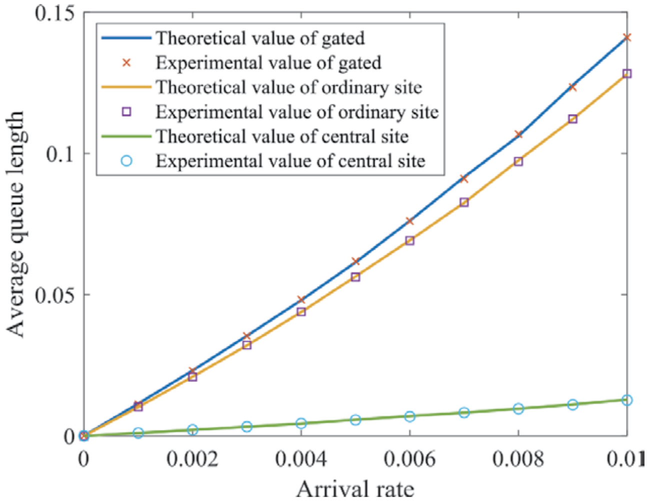

Figure 7.
Comparison of average queue length of two polling systems.

single-level model. It shows that the model not only distinguishes different priority business, but also optimizes the queue length and delay of ordinary sites, and improves the quality of service of the polling system.

4.2 Asymmetric two-level polling system

In WSNs, different stations handle different business, and the arrival rate of information packets, service time and polling conversion time are also different. To distinguish the business of different sites, an asymmetric two-level polling system is used to provide services. The performance analysis of the asymmetric system is shown below.

As can be seen in **Figures 9** and **10**, the average queue length of the ordinary sites and the central site is obviously affected by the service time, and the queue length increases with the service time. Similarly, the average queue length of the two stations with different priorities has a great difference, which shows that

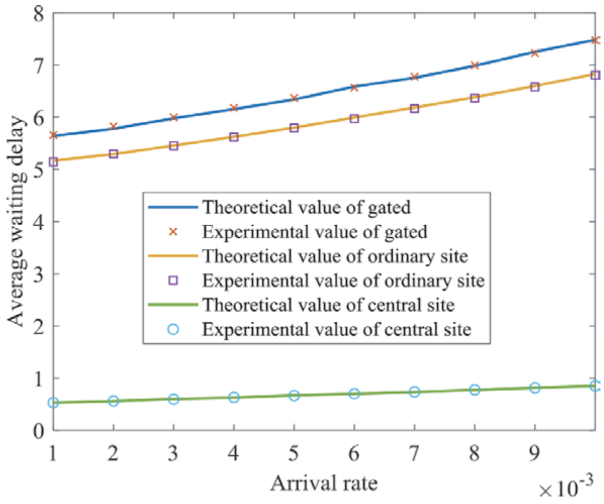

Figure 8.
Comparison of average waiting delay of two polling systems.

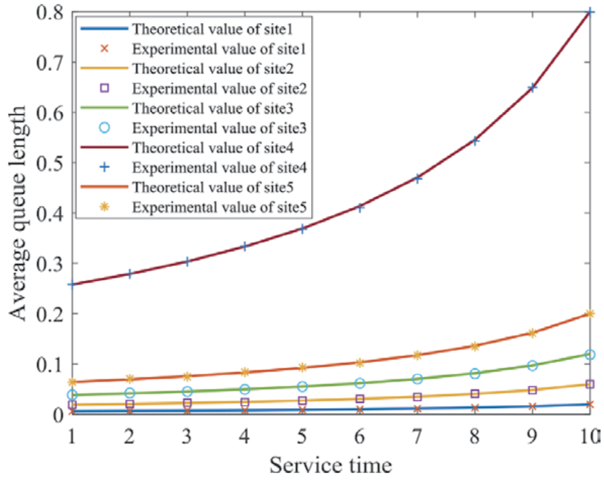

Figure 9.
Relationship between average queue length and service time of ordinary sites in asymmetric systems.

the priority of the polling system is well distinguished. In addition, the growth rate of the average queue length of the central station of 1 to h and 2 to h is relatively small compared with other sites. The main reason is that the arrival rate of each queue is different, which is consistent with the theoretical analysis. It can be seen from Eq. (19) that the queue length of the central station is directly proportional to the arrival rate, so when the arrival rate of the two stations is small, the impact on the queue length of the central station is small.

As can be seen from **Figures 11** and **12**, when the number of cycles selected is large, the theoretical value of the average waiting time is consistent with the experimental value. For the same system, when the service time of the system increases, the average waiting time also increases accordingly. In the case of the same load, the average waiting time of the central site is less than that of the ordinary sites, which indicates that it is effective to distinguish the business priority by using the mixed polling service mode. The performance of the system has been optimized as a whole.

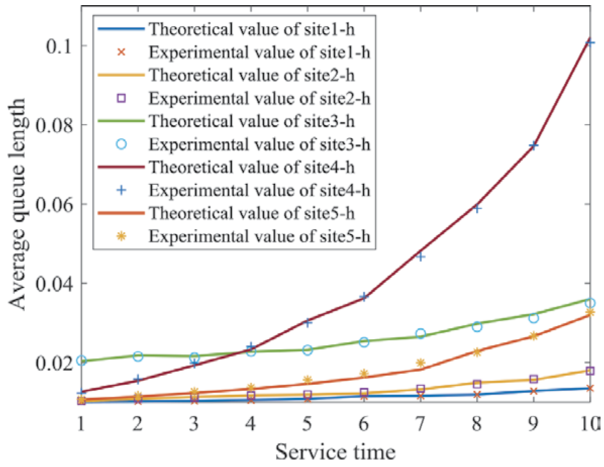

Figure 10.
Relationship between average queue length and service time of central site in asymmetric systems.

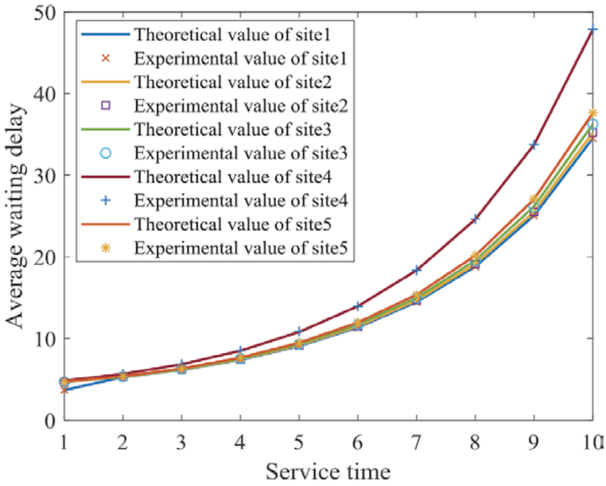

Figure 11.
Relationship between average waiting delay and service time of ordinary sites in asymmetric systems.

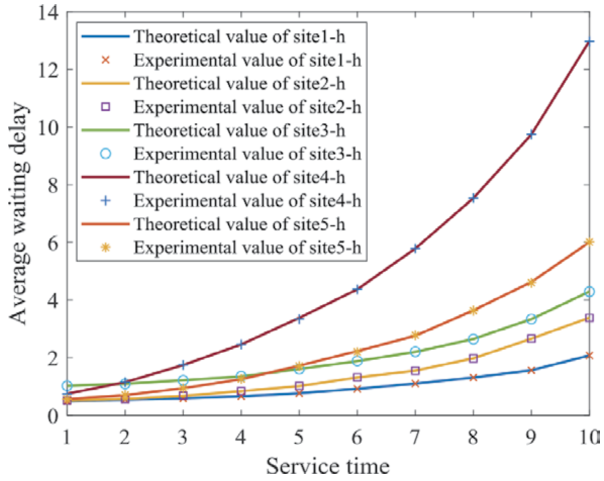

Figure 12.
Relationship between average waiting delay and service time of central site in asymmetric systems.

Arrival rate (λ)	Single-level gated		Single-level exhaustive		The model of literature [15]		Two levels of exhaustive-gated	
	$g_i(i)$	$E[w]$	$g_i(i)$	$E[w]$	$g_i(i)$	$E[w]$	$g_i(i)$	$E[w]$
0.01	0.0555	2.9467	0.0546	2.3211	0.0465	1.8293	0.0416	1.8024
0.02	0.1249	3.508	0.1206	2.7340	0.1075	2.2556	0.0960	2.2030
0.03	0.2143	4.2232	0.2018	3.2375	0.1736	2.7979	0.1611	2.6721
0.04	0.3342	5.1808	0.3071	3.9326	0.2517	3.4716	0.2453	3.3598
0.05	0.5013	6.5171	0.4482	4.8729	0.3723	4.6839	0.3600	4.2734

Table 1.
Comparison of queue length and delay of three models ($N = 5, \beta = 2, \gamma = 1$).

Table 1 shows the comparison of the average queue length and average delay (ordinary sites) between different models and the model proposed in this chapter, where the system is assumed to be symmetrical. It can be seen that whether compared with the single-level models or the other two-level models, the average queue length and delay of users in this model are smaller. It shows that the model proposed in this chapter not only distinguishes different priority business, but also has better performance.

5. Conclusion

In this book chapter, we adopt a prioritized polling system which combines exhaustive service with gated service, i.e., gated service is used in ordinary sites with low priority, and exhaustive service is used at central sites with high priority. Then a two-level priority service model is constructed by using the service mechanism of parallel pattern. The average queue length and average waiting delay of the service model are accurately analyzed by using embedded Markov chain and probability generating function, and verified by simulation experiments. The results show that the system can distinguish the business with different priorities, the average queue length and average waiting delay of users are lower, and the quality of service of the system is higher.

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Chapter 11

Cross-Layer Inference in WSN: From Methods to Experimental Validation

Indrakshi Dey

Abstract

In this chapter, the fundamentals of distributed inference problem in wireless sensor networks (WSN) is addressed and the statistical theoretical foundations to several applications is provided. The chapter adopts a statistical signal processing perspective and focusses on distributed version of the binary-hypothesis test for detecting an event as correctly as possible. The fusion center is assumed to be equipped with multiple antennas collecting and processing the information. The inference problem that is solved, primarily concerns the robust detection of a phenomenon of interest (for example, environmental hazard, oil/gas leakage, forest fire). The presence of multiple antennas at both transmit and receive sides resembles a multiple-input-multiple-output (MIMO) system and allows for utilization of array processing techniques providing spectral efficiency, fading mitigation and low energy sensor adoption. The problem is referred to as MIMO decision fusion. Subsequently, both design and evaluation (simulated and experimental) of these fusion approaches is presented for this futuristic WSN set-up.

Keywords: MIMO, decision fusion, distributed MAC, statistical CSI, instantaneous CSI, large-scale WSN, environmental characterization, experimental validation

1. Introduction

This chapter addresses the fundamentals of distributed inference problems in wireless sensor networks (WSNs) and provides statistical theoretical foundations to several applications. It adopts a statistical signal processing perspective and focuses on the distributed version of the binary-hypothesis test for detecting an event as correctly as possible. The reference WSN scenario is described in Section 2 which consists of multiple transmit sensors and an information center equipped with multiple antennas for collecting and processing the information to arrive at a robust decision on an observed phenomenon of interest. The presence of multiple antennas at both transmit and receive side resembles a multiple-input-multiple-output (MIMO) system and the inference problem based on information fusion is referred to as MIMO decision fusion. Consequently, several channel-aware fusion rules guiding MIMO decision fusion (DF) is studied in Section 3. The practical implications of employing MIMO decision fusion for distributed inference in WSN is evaluated through an indoor-to-outdoor measurement campaign detailed in Section 4. Performance of the fusion rules over the measured environment is also compared with that over the simulated set-up in Section 4.

2. WSN scenario and system model

In a WSN, decision fusion (DF) refers to the process of arriving at a final decision on an observed phenomenon by fusing local decisions transmitted by individual sensors on the said occurrence at a decision fusion center (DFC). In traditional WSNs, each sensor is allocated a dedicated orthogonal channel for transmitting their local observations, a communication scenario commonly referred to as parallel access channel (PAC) [1]. Sensor signals are transmitted over the PAC using time, frequency or code division multiple access. Over the recent years, large-scale or massive WSNs are being deployed, that involves coexistence of multitude of sensors, and the bandwidth requirement increases linearly with the number of sensors. In such scenarios, all sensors transmit their decisions simultaneously over a multiple access channel (MAC), while suffering from intrinsic interference resulting from superposition of multiple sensor signals in time [2]. To alleviate fusion performance in presence of deep fading, shadowing and interference, a DFC equipped with multiple antennas is proposed in [3]. This choice demands only further complexity on DFC side and does not affect simplicity of sensors implementation. The result is a communication over a “virtual” MIMO channel between the sensors and the DFC, as shown in **Figure 1**.

2.1 System model for MIMO configuration

2.1.1 Sensing and local decision model

A WSN consisting of S sensors and a DFC equipped with N receive antennas is considered for investigation in this section, where the sth sensor communicates its local decision, d_s, about the presence or absence of a target, after being mapped on an On-and-Off Shift Keying (OOK) [4] modulated symbol, $x_s \in X = \{0,1\}$. Irrespective of the scenario and target, $\mathrm{d}_s = \mathcal{H}_i$ maps into $x_s = i, i \in \{0,1\}$, where $\mathcal{H}_i \triangleq \{\mathcal{H}_0, \mathcal{H}_1\}$ is the set of binary hypotheses with $\mathcal{H}_0/\mathcal{H}_1$ representing the absence or presence of a specific target. The sensor decisions are assumed to be transported over a flat fading multiple access distributed (or virtual) MIMO channel with perfect synchronization at the receiver end.

The performance of WSN can be evaluated in terms of the conditional probability mass function (pmf) $P(\mathbf{x}|\mathcal{H}_i)$. Assuming conditionally independent and identically distributed (iid) decisions, we denote the probability of detection $P_{D,s} = P_{1,s}$ (or $P_D = P_1$) and false alarm $P_{F,s} = P_{0,s}$ (or $P_F = P_0$) at the sth sensor.

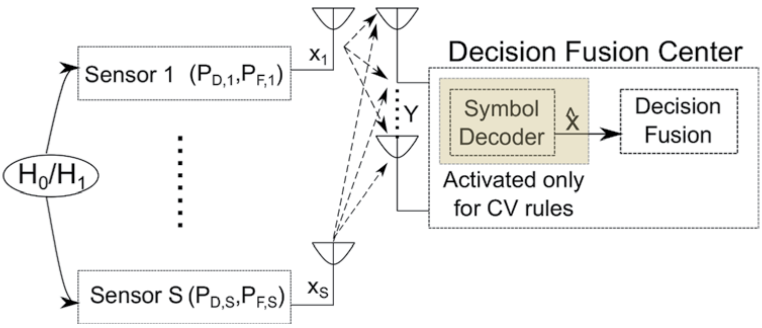

Figure 1.
Virtual MIMO based DF in WSN.

We also assume that $P_{D,s} \geq P_{F,s}$, i.e. the decision taken by individual sensor always results in a receiver operating characteristics (ROC) higher than the decision threshold γ. The system probabilities of false alarm and correct detection is given by,

$$P_{F_0} \overset{\Delta}{=} P(\Lambda > \gamma | \mathcal{H}_0) \qquad \text{for False Alarm} \tag{1}$$

$$P_{D_0} \overset{\Delta}{=} P(\Lambda > \gamma | \mathcal{H}_1) \qquad \text{for Correct Detection.} \tag{2}$$

where Λ is the fusion statistics, γ is the decision threshold to which Λ is compared to, and $P(A|B)$ is the probability of event A conditioned on event B.

2.1.2 Signal model

If the composite channel coefficient between the sth sensor and the nth receive antenna at the DFC is denoted by $\sqrt{b_{s,s}} h_{n,s}$, the received signal can be expressed as,

$$\mathbf{y} = \mathbf{H}\sqrt{\mathbf{B}}\mathbf{x} + \mathbf{w} \tag{3}$$

after sampling and matched filtering at the DFC, where $\mathbf{y} \in \mathbb{C}^N$ is the received signal, $\mathbf{x} \in X^S$ is the transmitted signal, $\mathbf{w} \sim \mathcal{N}_C(\mathbf{0}_N, \sigma_w^2 \mathbf{I}_N)$ is the additive white Gaussian noise (AWGN) vector, $\mathbf{H} \in \mathbb{C}^{N \times S}$ is the independent small scale fading matrix, $\mathbf{B} \in \mathbb{C}^{S \times S}$ is the large scale attenuation and shadowing matrix with the sth diagonal element $\mathbf{B} \overset{\Delta}{=} \text{diag}\left([\beta_1, \beta_2, \ldots, \beta_S]^T\right)$ accounting for pathloss and shadowing experienced by the sth sensor. Here, $\mathcal{N}_{\mathbb{C}}\ (\lambda, \Sigma)$ denotes circular symmetric complex normal distribution with mean vector λ and covariance matrix Σ respectively.

2.1.3 Channel model

If the propagation channel is assumed to be Rician distributed, the fading vector at the sth sensor can be modeled as,

$$\mathbf{h}_s^{\text{Rice}} = \kappa_s \mathbf{u}(\phi_s) + \sqrt{1 - \kappa_s^2}\, \breve{\mathbf{h}}_s \tag{4}$$

where $\mathbf{u}(\cdot)$ is the steering vector, $\breve{\mathbf{h}}_s \sim \mathcal{N}_C(\mathbf{0}_N, \mathbf{I}_N)$ is the non-line-of-sight (NLOS) scattered component and $\kappa_s \overset{\Delta}{=} \sqrt{\frac{K_s}{1+K_s}}$ is the Rician K-factor between sth sensor and DFC. A Two Wave with Diffused Power (TWDP) [5, 6] distributed channel fading vector can be modeled by,

$$\mathbf{h}_s^{\text{TWDP}} = \frac{\mathbf{u}(\phi_s)}{2\pi} \int_0^{2\pi} \breve{\kappa}_s \,\mathrm{d}\alpha + \frac{1}{2\pi}\, \breve{\mathbf{h}}_s \int_0^{2\pi} \sqrt{1 - \breve{\kappa}_s^2}\, \mathrm{d}\alpha \tag{5}$$

where $\breve{\kappa}_s = \sqrt{\frac{K_s[1+\Delta_s \cos\alpha]}{1+K_s[1+\Delta_s \cos\alpha]}}$, Δ_s is the shape factor for the fading distribution. For double-Rayleigh (DR) [7] distributed fading vector, the channel coefficients can be expressed as,

$$\mathbf{h}_s^{\text{DR}} = \prod_{j=1}^{2} \breve{\mathbf{h}}_{s_j}. \tag{6}$$

with $\kappa_s = 0$ and no line-of-sight (LOS) components existing between the sensors and the DFC.

The sensors are uniformly deployed with distances from the DFC varying between $\mathrm{d_{min}}$ and $\mathrm{d_{max}}$, and large scale attenuation of $\beta_s = \nu_s \left(\frac{\mathrm{d_{min}}}{\mathrm{d}_s}\right)^{\eta_P}$ where η_P is the pathloss exponent and ν_s is a log-normal variable such that $10 \log_{10}(\nu_s) \sim \mathcal{N}\left(\mu_P, \sigma_P^2\right)$ with $\mathcal{N}\left(\hat{\lambda}, \hat{\Sigma}\right)$ representing normal distribution with mean vector $\hat{\lambda}$ and covariance matrix $\hat{\Sigma}$ respectively, d_s is the distance of the sth sensor from the DFC, μ_P and σ_P are the mean and standard deviations in dBm respectively.

2.1.4 Modified system model for non-coherent decision fusion

Non-coherent decision fusion over MAC using the received-energy test has been investigated in [2, 8]. In such a scenario, if the probability of false alarm for any sensor decision is lower than the probability of detection, the received energy can prove to be optimal for arriving at the right decision about an observed phenomenon at the DFC for mutually independent and identically distributed (i.i.d.) sensor decisions.

In this case, let us consider that a group of sensors transmit their local decisions to the DFC equipped with N antennas over a Raleigh faded MAC with channel coefficients of equal mean power, thereby exploiting diversity combining, either in time, frequency, code or in polarization domain. Statistical channel state information (CSI) is assumed at the DFC, i.e. only the pdf of each fading coefficient is available.

Let us denote: y_n the received signal at the nth diversity branch of the DFC after matched filtering and sampling; $h_{n,s} \sim \mathcal{N}_{\mathbb{C}}\left(0, \sigma_h^2\right)$, the fading coefficient between the sth sensor and the nth diversity branch of the DFC; w_n the additive white Gaussian noise at the nth diversity branch of the DFC. The vector model at the DFC is the following:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{7}$$

where $\mathbf{y} \in \mathbb{C}^N$, $\mathbf{x} \in X^S$ and $\mathbf{w} \sim \mathcal{N}_C\left(\mathbf{0}_N, \sigma_w^2 \mathbf{I}_N\right)$ are the received signal, transmitted signal and the AWGN vectors respectively. Finally, we define the random variable $l \triangleq l(x) = \sum_{s=1}^{S} x_s$, representing the number of active sensors and the set $\mathcal{L} \triangleq \{0, \ldots, S\}$ of possible realizations of l. It is worth-mentioning here that it will be more practical to assume an asymmetric model for the statistics of the channel coefficients resulting in scenario-dependent analysis. Therefore, symmetric channel model is considered here to analyze performance with power control possibility depending on the application scenario.

3. MIMO decision fusion

3.1 Instantaneous CSI

Two types of fusion rules are considered and compared in this chapter in order to arrive at a reliable choice depending on the communication scenario. One set of rules (Decode-and-Fuse) uses the received signal directly to arrive at a decision on whether a target is present or absent, without taking any information from the transmitted signal into consideration, the optimum (opt) test statistics [9] for which is given by,

$$\Lambda_{\text{opt}} = \ln\left[\frac{\sum_{\mathbf{x}\in X^S}\exp\left(-\frac{\left\|\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\mathbf{x}\right\|^2}{\sigma_w^2}\right)\prod_{s=1}^{S}P(x_s|\mathcal{H}_1)}{\sum_{\mathbf{x}\in X^S}\exp\left(-\frac{\left\|\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\mathbf{x}\right\|^2}{\sigma_w^2}\right)\prod_{s=1}^{S}P(x_s|\mathcal{H}_0)}\right] \tag{8}$$

assuming conditional independence of $\mathbf{y}$ from $\mathcal{H}_i$, given x_s, $\mathbf{H}\in\mathbb{C}^{N\times S}$ and $\mathbf{x}\in\mathbb{C}^{S\times 1}$. The test statistics for three different sub-optimum fusion rules belonging to this group are considered for this section to compensate for the asymptotically increasing computational complexity of the optimum rule. These rules are Maximal Ratio Combining (MRC) [10], Equal Gain Combining (EGC) [11] and Max-Log rules [12], defined by the following test statistics,

$$\Lambda_{\text{MRC}} \propto \Re\left(\mathbf{1}_S^t\left(\mathbf{H}\sqrt{\mathbf{B}}\right)^{\dagger}\mathbf{y}\right) \tag{9}$$

$$\Lambda_{\text{EGC}} = \Re\left(\left(e^{j\cdot\angle\left(\mathbf{H}\sqrt{\mathbf{B}}\,\mathbf{1}_S\right)}\right)^{\dagger}\mathbf{y}\right) \tag{10}$$

$$\begin{aligned}\Lambda_{\text{Max-Log}} = &\min_{\mathbf{x}\in X^S}\left[\frac{\left\|\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\mathbf{x}\right\|^2}{\sigma_w^2}-\sum_{s=1}^{S}P(x_s|\mathcal{H}_0)\right]\\ &-\min_{\mathbf{x}\in X^S}\left[\frac{\left\|\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\mathbf{x}\right\|^2}{\sigma_w^2}-\sum_{s=1}^{S}P(x_s|\mathcal{H}_1)\right]\end{aligned} \tag{11}$$

respectively, all assuming identical sensor performances.

The other set of fusion rules (Decode-then-Fuse) aims at concluding to a global decision after estimating the transmit signal from the received signal vector. Using Chair-Varshney (CV) rule, the test statistics for which over a noiseless channel is given by,

$$\Lambda_{\text{CV}} = \sum_{s=1}^{S}\left[\hat{\Pi}_s\ln\left(\frac{P_{D,s}}{P_{F,s}}\right)+\left(1-\hat{\Pi}_s\right)\ln\left(\frac{1-P_{D,s}}{1-P_{F,s}}\right)\right] \tag{12}$$

where $\hat{\Pi}_s \triangleq \frac{\hat{x}_s+1}{2}$. Two different detectors are considered under this umbrella, especially, the Maximum Likelihood (ML) detector [13] to obtain,

$$\hat{\mathbf{x}}_{\text{ML}} = \arg\min_{\mathbf{x}\in X^S}\left\|\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\mathbf{x}\right\|^2 \tag{13}$$

and the Minimum Mean-Squared Error (MMSE) detector [14] to get,

$$\hat{\mathbf{x}}_{\text{MMSE}} = \text{sign}\left[\overline{\mathbf{x}}+\mathbf{C}\left(\mathbf{H}\sqrt{\mathbf{B}}\right)^{\dagger}\left(\left(\mathbf{H}\sqrt{\mathbf{B}}\right)\mathbf{C}\left(\mathbf{H}\sqrt{\mathbf{B}}\right)^{\dagger}+\sigma_w^2\mathbf{I}_N\right)^{-1}\left(\mathbf{y}-\mathbf{H}\sqrt{\mathbf{B}}\overline{\mathbf{x}}\right)\right] \tag{14}$$

where $\overline{\mathbf{x}} = \mathrm{E}\{\mathbf{x}\}$ and $\mathbf{C} \triangleq \left\{(\mathbf{x}-\overline{\mathbf{x}})(\mathbf{x}-\overline{\mathbf{x}})^{\dagger}\right\}$ are the mean and covariance matrix of the transmit signal vector respectively. The estimated $\hat{\mathbf{x}}$ from the above two detectors can be incorporated directly in the CV-rule of (12) to obtain the test statistics for CV-ML and CV-MMSE rules.

3.2 Statistical CSI

If statistical CSI [15] is used for DF at the receiver instead of the instantaneous CSI extracted from the sensor signals received at the DFC, the optimal test statistics can be formulated as,

$$\Lambda_{\text{opt}} \triangleq \ln\left[\frac{p(\mathbf{y}|\mathcal{H}_1)}{p(\mathbf{y}|\mathcal{H}_0)}\right] \quad \begin{matrix} \hat{\mathcal{H}} = \mathcal{H}_1 \\ > \\ < \\ \hat{\mathcal{H}} = \mathcal{H}_0 \end{matrix} \; \gamma \tag{15}$$

where $\hat{H}$ is the estimated hypothesis, Λ_{opt} is the Log-Likelihood-Ratio (LLR) of the optimal fusion rule and γ is the decision threshold to which Λ_{opt} is compared to. The threshold can be determined using either the Bayesian approach (i.e. the threshold is detected based on the one that minimizes the probability of error) or the Neyman-Pearson approach [16] (i.e. the threshold is detected based on the one that ensures fixed system false-alarm rate). An explicit expression of the LLR from Eq. (15) is given by,

$$\Lambda_{\text{opt}} = \ln\left[\frac{\sum_{l=0}^{S} \frac{1}{\left(\sigma_w^2+\sigma_h^2\right)^N} \exp\left(-\frac{\|\mathbf{y}\|^2}{\sigma_w^2+\sigma_h^2}\right) P(l|\mathcal{H}_1)}{\sum_{l=0}^{S} \frac{1}{\left(\sigma_w^2+\sigma_h^2\right)^N} \exp\left(-\frac{\|\mathbf{y}\|^2}{\sigma_w^2+\sigma_h^2}\right) P(l|\mathcal{H}_0)}\right] \tag{16}$$

where we have exploited the conditional independence of $\mathbf{y}$ from $\mathcal{H}_i$ (given l).

In the case of conditionally (given $\mathcal{H}_i$) i.i.d. sensor decisions ($(P_{D,s}, P_{F,s}) = (P_D, P_F), s \in S$) we have that $l|\mathcal{H}_1 \sim \mathcal{B}(S, P_D)$ and $l|\mathcal{H}_0 \sim \mathcal{B}(S, P_F)$. Differently, when local sensor decisions are conditionally i.n.i.d. the pmfs $P(l|\mathcal{H}_i)$ are represented by the more general Poisson-Binomial distribution with expressions given by,

$$\begin{aligned} P(l|\mathcal{H}_1) &= \sum_{x:x(l)=l} \prod_{s=1}^{S} (P_{D,s})^{x_s} \prod_{u=1}^{S} (P_{D,u})^{(1-x_u)} \\ P(l|\mathcal{H}_0) &= \sum_{x:x(l)=l} \prod_{s=1}^{S} (P_{F,s})^{x_s} \prod_{u=1}^{S} (P_{F,u})^{(1-x_u)} \end{aligned} \tag{17}$$

It is to be noted here that calculating the sums in Eq. (17) practically becomes impossible with the increase in the number of sensors S. Several alternatives have been proposed across literature to tackle such exhaustive computations, which include fast convolution of individual Bernoulli probability mass functions (pmfs) [17], Discrete Fourier Transform (DFT) [18] based computation and recursion-based iterative approaches.

4. Performance evaluation of MIMO decision fusion

4.1 Measurement campaigns

An indoor-to-outdoor measurement campaign has been conducted in [19] for investigating propagation characteristics of an 8 × 8 (number of sensors S = number of receive antennas at the DFC N) virtual MIMO system at 2.53 GHz with 20 MHz bandwidth and subcarrier spacing of around 0.15 MHz. The campaign is conducted with different spatial combinations of half-omnidirectional single transmit antennas representing the sensors, deployed in two different rooms of the Facility of Over-the-Air Research and Testing (FORTE) at Fraunhofer IIS in Ilmenau, Germany (Conference Room, $\mathcal{C}$, located on the 1st floor and Instrumentation Room, $\mathcal{I}$, located on the ground floor) and receive antennas mounted and co-located on an outside tower representing the DFC. The antennas emulating the sensors are deployed at different heights, namely, near the ground and ceiling and at heights of 1meter (m), 1.5 m and 2 m from the ground, sometimes on all 4 walls, sometimes on all 3 walls and sometimes only on 1 wall of each room at a time. The channel measurements are collected over a measurement set-up detailed in **Figure 2** and are recorded using the MEDAV RUSK - HyE MIMO channel sounder.

The dimensions of the two rooms selected are 8.45 m by 4.52 m by 2.75 m for the $\mathcal{C}$ room and 5.7 m by 3.5 m by 3 m for the $\mathcal{I}$ room. These rooms are chosen such that a variety of indoor environments is represented including $\mathcal{I}$ room with keyhole effect (no windows) and with no direct LOS communication, $\mathcal{C}$ room (smart office) and room cluttered with several noisy electrical and metering equipment (potential scenario for Industry 4.0). In both rooms, measurement set-up is repeated for stationary scenarios and scenarios with people moving around. Due to channel reciprocity conditions, it is assumed that channel estimates can be used for both uplink and downlink.

4.2 Environment characterization

Large and small scale channel statistics are extracted from the channel impulse response (CIRs) and channel frequency responses (CFRs) recorded in the above-mentioned campaign. In order to separate out large scale statistics, average received power and attenuation at each measurement location is calculated by averaging the recorded CIRs at that location. The pathloss exponent is determined from the slope of the best fit line to the logarithm of distances v/s logarithm of average attenuation plot. The probability density function (pdf) of deviation of each value of calculated attenuation from the best-fit line to the log–log plot yields the shadowing distribution. **Figures 3–5** demonstrates the log–log attenuation plots for three different measurement scenarios, static environment - Conference ($\mathcal{SC}$), dynamic environment - Conference ($\mathcal{DC}$) and static environment - Instrumentation ($\mathcal{SI}$) rooms respectively, while **Table 1** summarizes the average values for the pathloss exponents (η_P) and mean and standard deviation (μ_P, σ_P) of the shadowing distributions in all the three above-mentioned measurement scenarios.

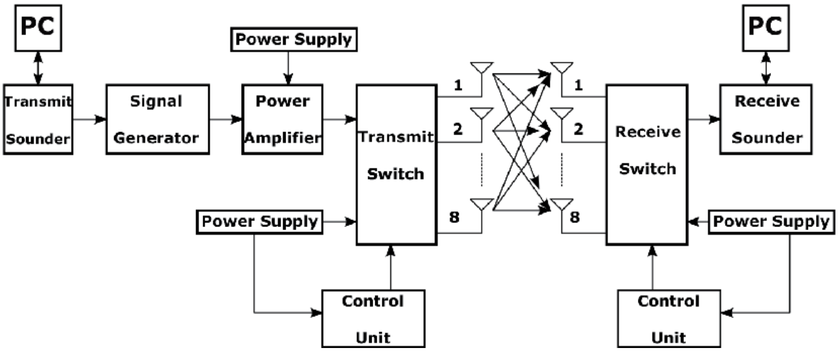

Figure 2.
Block diagram of measurement set-up.

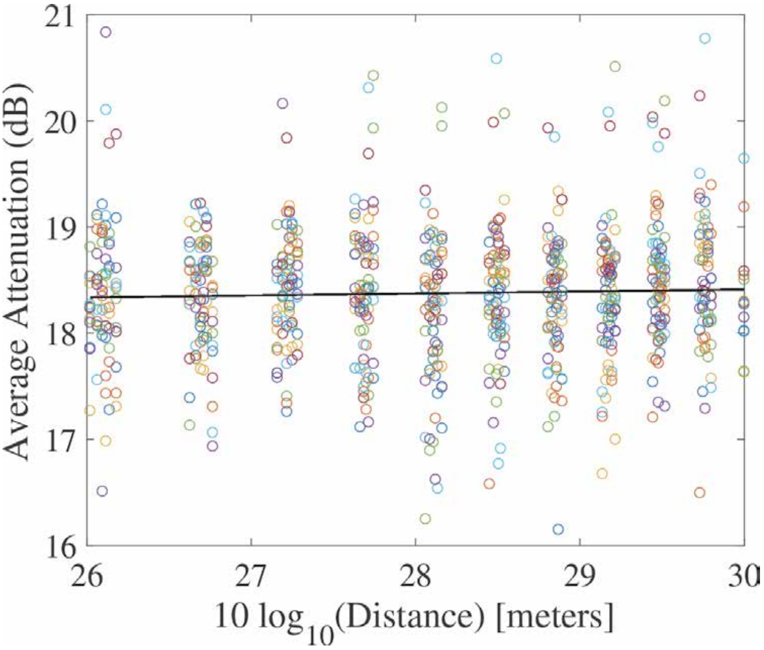

Figure 3.
Log average attenuation versus log distance for conference - static environment.

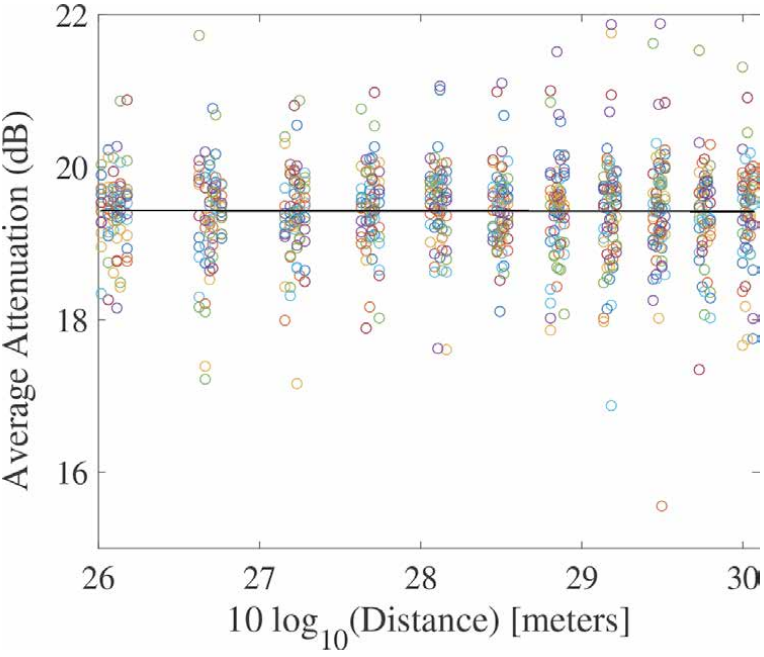

Figure 4.
Log average attenuation versus log distance for conference - dynamic environment.

The gamma distribution with mean of $-1 \sim 6$ dB and standard deviation of $-5 \sim 5$ dB offers a good approximation to the shadowing experienced in the campaign. The pathloss exponent varies between 2 to 4. Higher η_P is experienced over a shorter distance direct link between the sensors and the DFC. Lower shadowing is observed in an environment ($\mathcal{I}$ room) cluttered with metallic surfaces that

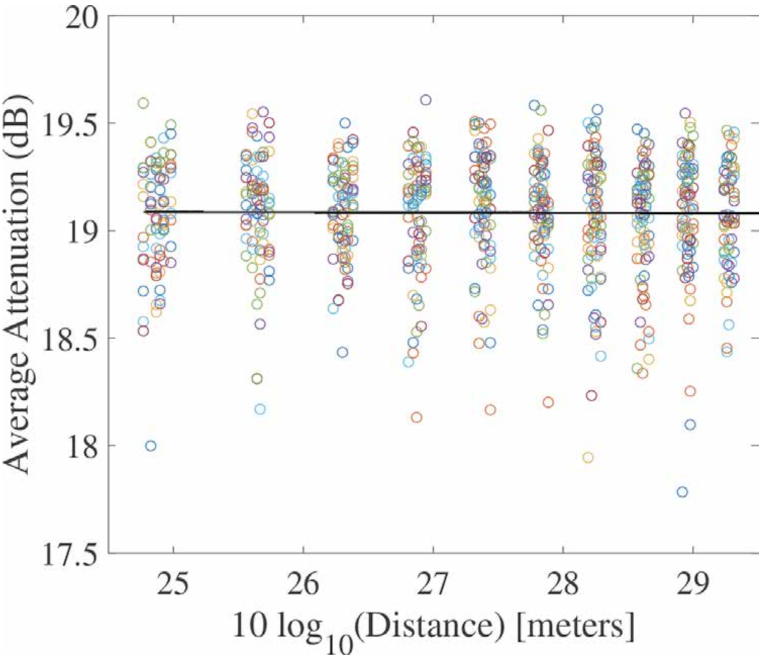

Figure 5.
Log average attenuation versus log distance for instrumentation - static environment.

Scenario	η_P	μ_P(dB)	σ_P(dB)
$\mathcal{SC}$	2.72	1.22	2.4
$\mathcal{SI}$	3.96	1.48	1.89
$\mathcal{DC}$	2.56	1.77	3.6

Table 1.
Large scale parameters.

contribute constructively to reflected signal power than in an open indoor environment ($\mathcal{C}$ room) stocked with wooden tables and chairs.

To analyze the small scale channel statistics, the power delay profile (PDP) of the channel is drawn by averaging the power across all the delay bins for each sensor (**Table 2**). The average delay spread is the first moment and the root mean square (rms) delay spread is the square root of the second central moment of each sensor channel PDP respectively. The fading vector is obtained by concatenating CFRs at all the frequency points experienced over each sensor-DFC channel. The number of frequency points encountered is calculated by dividing the discrete bandwidth of the measured signal with the discrete coherence bandwidth of the sensor-DFC channel. The measurement is also used to deduce additional details like

Scenario	K	Δ	$\xi_{e,f}$	$\mathcal{A}$
$\mathcal{SC}$	2.5424	0	0.6511	7.64
$\mathcal{SI}$	1.1217	0	0.5877	3.8158
$\mathcal{DC}$	8.5287	0.6004	0.41	4.5227

Table 2.
Small scale parameters [19].

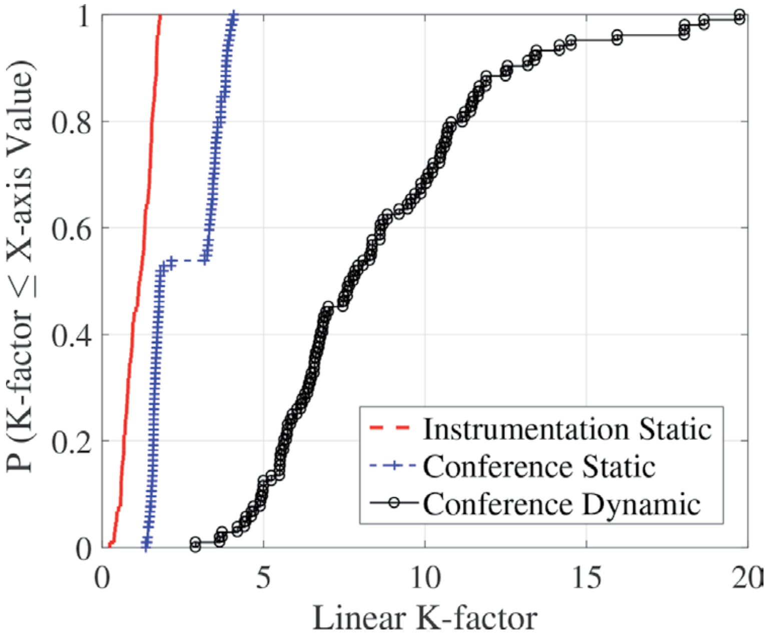

Figure 6.
CDF of K-factor for all environments.

antenna correlation, determined from the correlation coefficients between each pair of fading vectors. The phase information from the complex CIRs is used to compute the steering vector for each transmit antenna.

The distribution of the derived fading vector fits the Rician distribution in most cases, with DR and TWDP distributions fitting the remaining few. **Figure 6** demonstrates the range of K-factor values for the Rician and TWDP distribution fitting and **Figure 7** plots the range of Δ values good for the TWDP distribution fitting where Δ-factor arises due to the presence of two strong interfering components and is given by $\Delta = \frac{2V_1V_2}{V_1^2+V_2^2} \sim 0$ to 1, with V_1 and V_2 are the instantaneous amplitudes of the specular components. **Figures 8** and **9** depicts the range of antenna correlation coefficients and amount-of-fading (AF) values experienced over all the measurement scenarios, respectively. The average values for each of channel parameters, K, Δ, correlation coefficients, $\xi_{\mathfrak{e},\mathfrak{f}}$ and AF ($\mathcal{A}$) obtained after analysis of the measurement data over each measurement scenarios of $\mathcal{SC}$, $\mathcal{DC}$ and $\mathcal{SI}$.

A special scenario is observed in case of the $\mathcal{I}$ room where the propagation environment can be approximated by DR fading ($K = 0$) distribution. As the $\mathcal{I}$ room is devoid of any windows, a rich scattering environment with 'keyhole' effect [20] is experienced with the existence of a waveguide propagation channel.

In the dynamic scenario, two sets of specular multipath components arrive at the receiver, one over the direct LOS link and the other due to reflection from the moving human body, thereby yielding en environment which can be accurately approximated by the TWDP fading distribution with K values ranging between 6 and 20 and Δ values varying between 0.1 and 0.9. Large distances between the transmit sensor and the DFC and nearness of most of the scattering surfaces to the sensors has resulted in similar AF values over all the measurement scenarios (refer to **Figure 9**).

Rich scattering and diffraction around the sensors in the windowless $\mathcal{I}$ room has resulted in low correlation between the transmitted signals, while a high correlation is observed among the sensor signals in the open environment of the $\mathcal{C}$ room. In

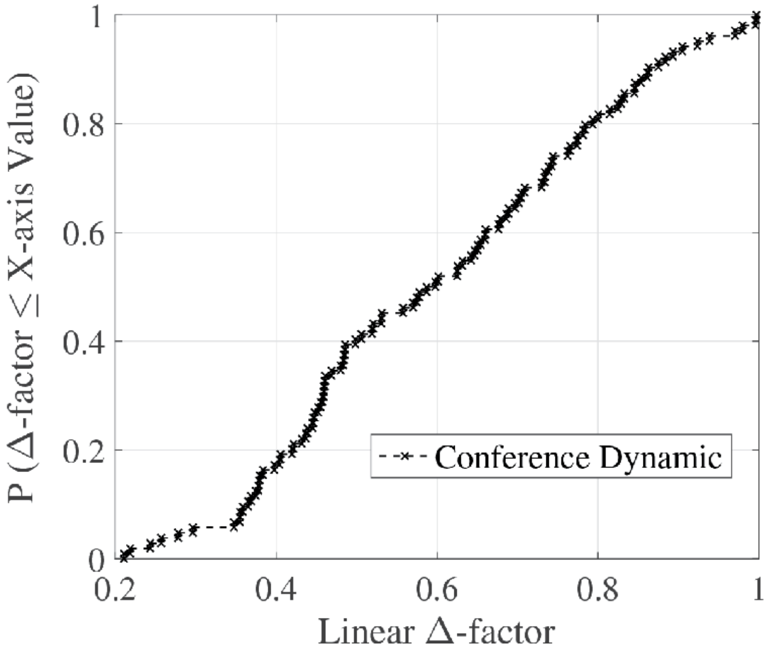

Figure 7.
CDF of Δ for the dynamic environment in the conference room.

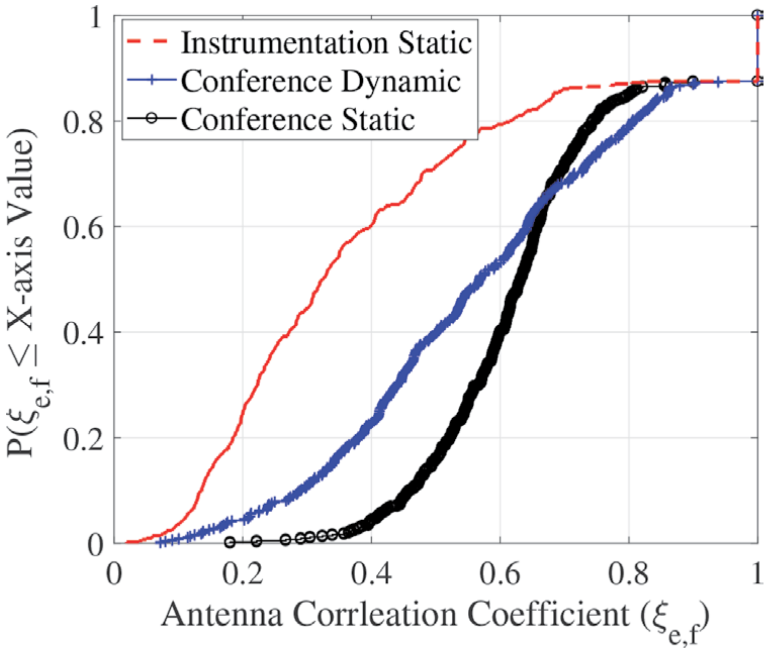

Figure 8.
CDF of antenna correlation coefficient for all environments.

summary, both fading and shadowing gets detrimental with the increase in inter-sensor distances. Separation between the sensors leads to very low coordination between them making the transmit signals vulnerable to noise, interference and fading, while a large number of different shadowing values are encountered resulting in higher shadowing variance and increased shadowing severity. For

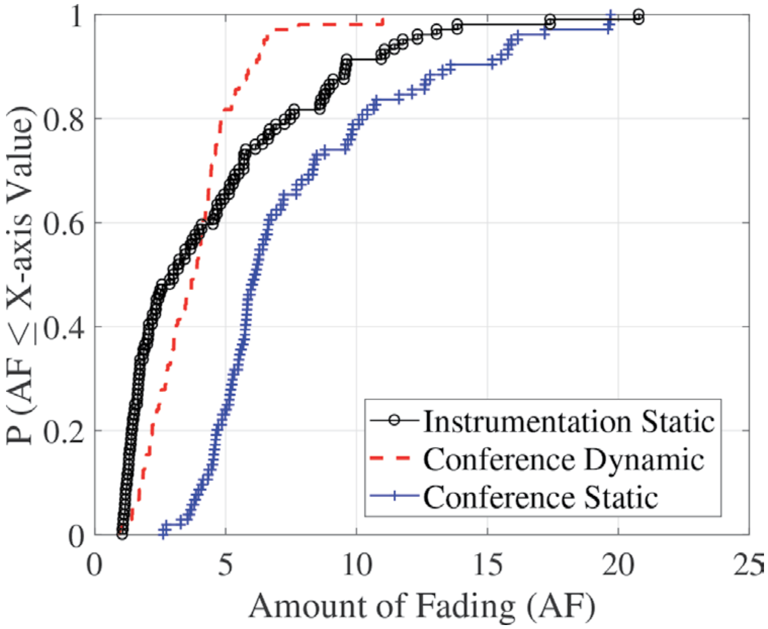

Figure 9.
CDF of amount of fading (AF) for all environments.

Scenario	K	Δ
$\mathcal{SC}$	0.5 to 4	—
$\mathcal{SI}$	0	—
$\mathcal{DC}$	6 to 20	0.1 to 0.9

Table 3.
Generalized range of values small scale parameters.

indoor-to-outdoor virtual MIMO based communication scenario in WSNs, the propagation environment can experience a K-factor varying between 0 to 20 and a Δ-value varying between 0.1 to 0.9 in an open-concept smart office or home and in industry-like environments, as compiled in **Table 3**.

4.3 Performance analysis

The fusion performance of the formulated sub-optimum fusion rules is evaluated in this subsection, where the propagation environment is modeled using the accumulated measurements. Based on the observation in $\mathcal{SC}$, $\mathcal{DC}$ and $\mathcal{SI}$ experimental scenarios, Ricean, TWDP and DR distributions are used to characterize the propagation channel.

4.3.1 Receiver operating characteristics (ROC)

For the different fusion rules of Section 3, probability of detection (P_{D_0}) is plotted against probability of false alarm (P_{F_0}) (commonly referred to as the Receiver Operating Characteristics (ROC)) for $S = 8$ and $N = 8$ in presence of a fixed channel SNR of 20 dB. The particular value of 20 dB is chosen for the plots, as the average attenuation $\mathbf{A}(i)$ recorded for any measurement location i is approximately around 20 dB across all measurement environments. The measured SNR over the direct LOS link is recorded to be equal to 40 dB yielding an equivalent channel SNR of $(40 - 20) = 20$ dB.

- *Impact of large scale channel parameters*: In order to analyze the impact of large scale channel effects, the small scale fading vectors are modeled to be Rayleigh distributed ($\mathbf{h}_{n,s} \sim \mathcal{N}_{\mathbb{C}}(0, 1)$). From the Decode-and-Fuse group of sub-optimum fusion rules, MRC and Max-Log are used for DF over four different communication scenarios; No Shadowing ('Th'; η_P, μ_P, σ_P = 1, 0 dB, 0 dB; $\mathbf{h}_{n,s} \sim \mathcal{N}_{\mathbb{C}}(0, 1)$), $\mathcal{SC}$ (η_P, μ_P, σ_P = 2.72, 1.22 dB, 2.4 dB), $\mathcal{DC}$ (η_P, μ_P, σ_P = 2.56, 1.77 dB, 3.6 dB), $\mathcal{SI}$ (η_P, μ_P, σ_P = 1.96, 1.48 dB, 1.89 dB), and the ROC performances are plotted in **Figure 10**.

With increase in shadowing and pathloss, MRC outperforms Max-Log. Dependence of Max-Log rule on the noise spectral density σ_w^2 is the principle reason behind its poor performance in presence of rich shadowing. From the second group, CV-ML and CV-MMSE rules are used for DF over the above-mentioned four communication scenarios and the ROC performances are plotted in **Figure 11**. With increase in large scale channel effects, CV-MMSE outperforms CV-ML. The propagation environment has no impact on the performance of CV-ML owing to its dependence only on the SNR which is kept constant for the plots in **Figure 11**. In general, sub-optimum fusion rules perform better over $\mathcal{SC}$ scenario than over $\mathcal{DC}$ and over $\mathcal{DC}$ than over $\mathcal{SI}$. With a strong LOS link existing in case of the $\mathcal{SC}$ scenario, it experiences the lowest pathloss. The $\mathcal{DC}$ scenario experiences higher pathloss due to penetration losses contributed by the moving human bodies.

- *Impact of small scale channel parameters*: In order to analyze the effect of the small scale channel effects, sub-optimum fusion rules are used for DF over four different communication scenarios;

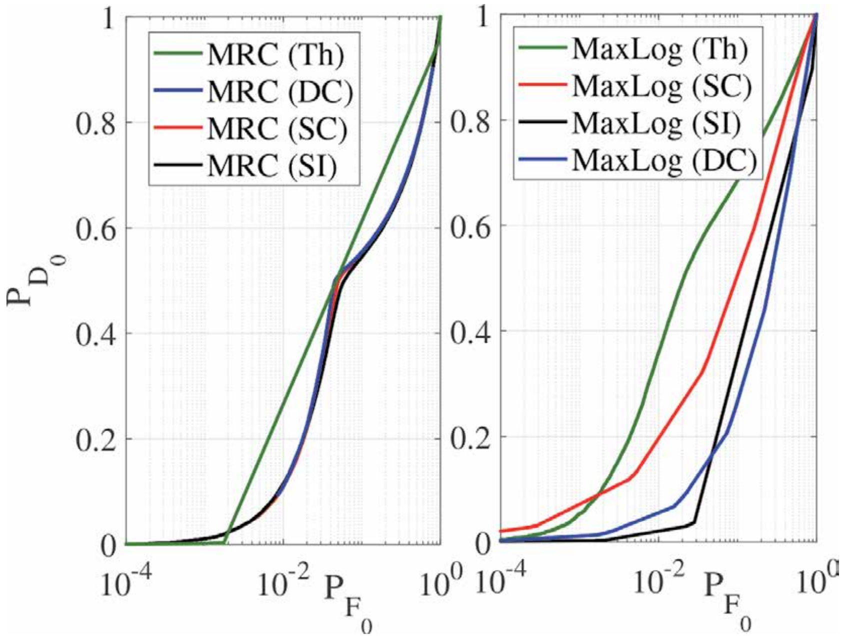

Figure 10.
Comparative ROC for the first group of fusion rules for different measured large scale parameters (varying η_P, μ_P and σ_P) with $S = 8$, $N = 8$ and Rayleigh distributed fading vector. Results for no shadowing condition, denoted by 'Th' are also plotted for comparison.

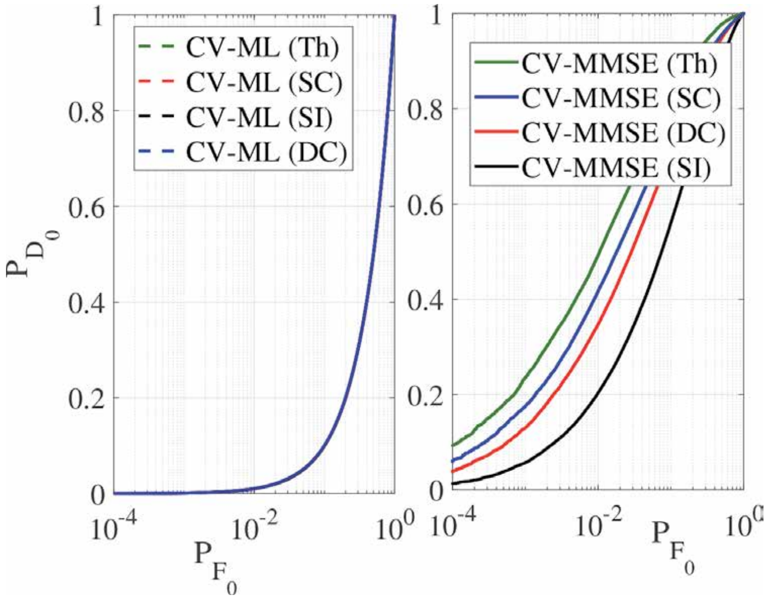

Figure 11.
Comparative ROC for the second group of fusion rules for different measured large scale parameters (varying η_P, μ_P and σ_P) with $S = 8$, $N = 8$ and Rayleigh distributed fading vector. Results for no shadowing condition, denoted by 'Th' are also plotted for comparison.

1. 'Th' case with Rayleigh distributed fading vectors (η_P, μ_P, σ_P = 1, 0 dB, 0 dB; $\mathbf{h}_{n,s} \sim \mathcal{N}_{\mathbb{C}}(0,1)$),

2. $\mathcal{SC}$ scenario with Rician distributed fading vectors (η_P, μ_P, σ_P = 2.72, 1.22 dB, 2.4 dB; $\mathbf{h}_s^{\text{Rice}}$ with $[K_{s,\min}, K_{s,\max}] = [0.5, 4]$),

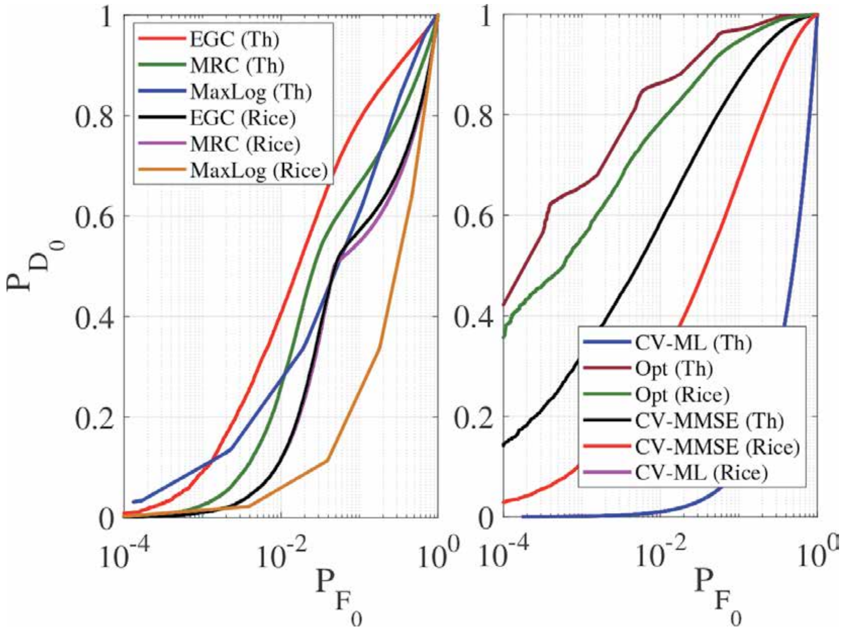

Figure 12.
Comparative ROC for all fusion rules for the $\mathcal{SC}$ environment with $S = 8$, $N = 8$ in Rician fading condition. Results for Rayleigh fading-only condition ('Th') are plotted for comparison.

3. $\mathcal{DC}$ scenario with TWDP fading vectors (η_P, μ_P, σ_P = 2.56, 1.77 dB, 3.6 dB; $\mathbf{h}_s^{\text{TWDP}}$ with $[K_{s,\min}, K_{s,\max}] = [6, 20]$, $[\Delta_{s,\min}, \Delta_{s,\max}] = [0.1, 0.9]$),

4. $\mathcal{SI}$ scenario with DR fading vectors (η_P, μ_P, σ_P = 1.96, 1.48 dB, 1.89 dB; $K_s = 0$),

and the ROC performances are plotted in **Figures 12–14** respectively.

If the small scale fading vectors are Rayleigh distributed, EGC performs best and CV-ML performs worst. CV-ML is worst under all considered propagation scenario. Max-Log performs a tad bit better than CV-ML over Rician, TWDP and DR fading channels. If the fading vectors are Rician and TWDP distributed, MRC, EGC and CV-MMSE perform almost equivalently. CV-MMSE however champions over MRC and EGC if the small scale channel effects follow DR distribution. Some analogies between performances under measured environment and simulated (as in [21]) can also be concluded from the results presented in **Figures 10–14**. In both cases ROC performance demonstrates that CV-MMSE performs better than CV-ML rule, CV-MMSE performs close to MRC/EGC rules, while CV-ML exhibits the worst performance.

4.3.2 P_{D_0} v/s N

In **Figures 15** and **16**, we show system probabilities of detection, P_{D_0} with two groups of fusion rules as an interpolated function of the number of receive antennas N under $P_{F_0} \leq 0.01$.

- *Impact of measurement environment*: If both large and small scale channel parameters are varied, the probability of detection P_{D_0} with MRC and CV-MMSE rules saturates with the increase in N over the $\mathcal{SC}$ scenario, but increases

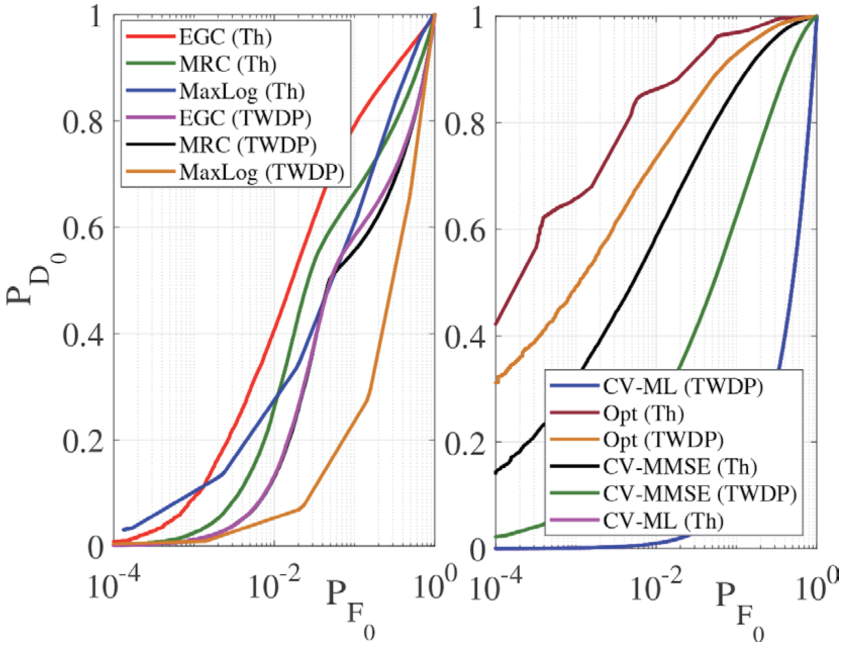

Figure 13.
Comparative ROC for all fusion rules for the $\mathcal{DC}$ environment with $S = 8$, $N = 8$ in TWDP fading condition. Results for Rayleigh fading-only condition ('Th') are plotted for comparison.

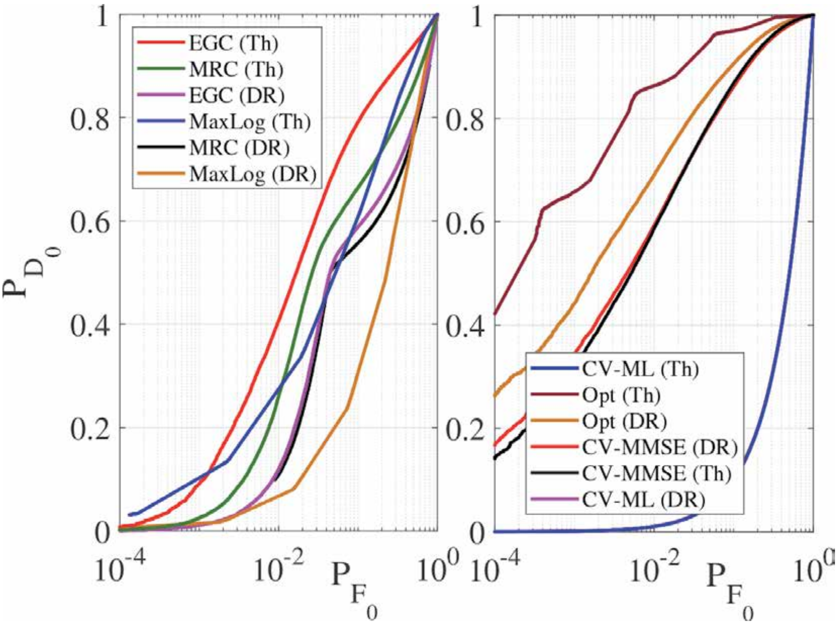

Figure 14.
Comparative ROC for all fusion rules for the $\mathcal{SI}$ environment with $S = 8$, $N = 8$ in double-Rayleigh (DR) fading condition. Results for Rayleigh fading-only condition ('Th') are plotted for comparison.

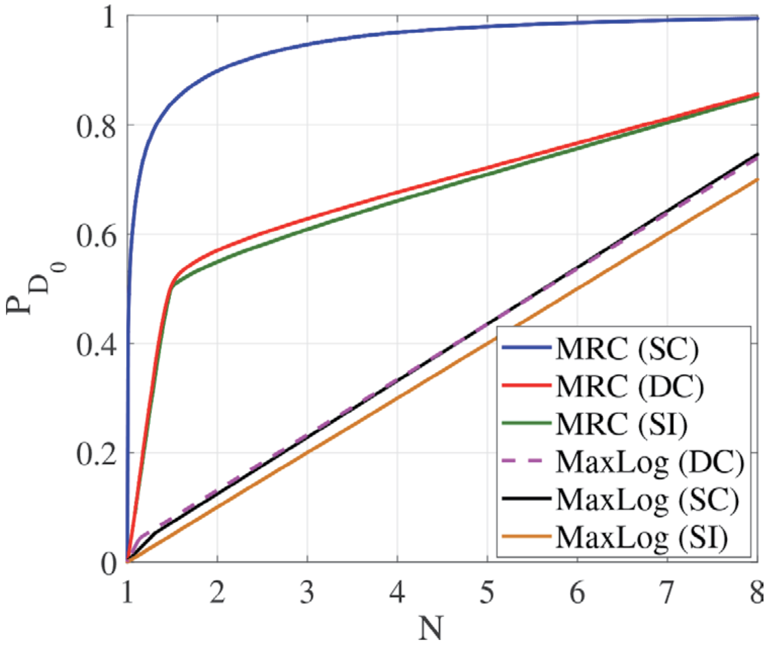

Figure 15.
P_{D_0} v/s N for the first group of fusion rules with $S = 8$ for different measurement environments reflecting the impact of both large scale and small scale channel parameters.

with N for the $\mathcal{DC}$ and $\mathcal{SI}$ scenarios at a rate slower with higher N, as is evident in **Figures 15** and **16**. P_{D_0} with CV-ML and Max-Log rules increases proportionately with N for all scenarios. It is worth-mentioning that this set of performances is limited to the chosen channel of 20 dB, and cannot be generalize to any value of channel SNR.

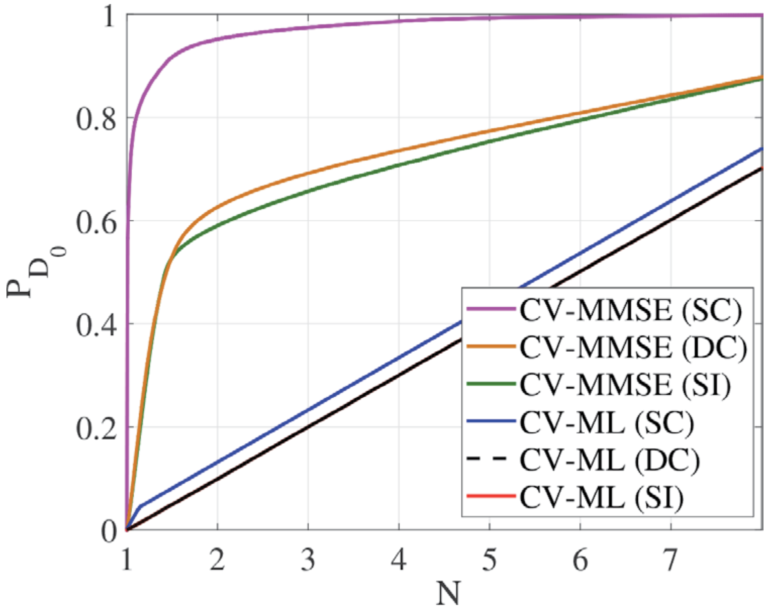

Figure 16.
P_{D_0} v/s N for the second group of fusion rules with $S = 8$ for different measurement environments reflecting the impact of both large scale and small scale channel parameters.

5. Conclusions

This chapter summarizes design of sub-optimal fusion rules propounded for decision fusion at a DFC equipped with multiple antennas. Such rues are more efficient than exact LLR based optimal fusion rule for practical implementation. The sub-optimal fusion rules offer a plethora of choices for fusing sensor decisions at the DFC energy efficiently with lower requirement of system knowledge and computational complexity, thereby eliminating all problems with fixed point implementation. All these rules still significantly benefit from the addition of multiple antennas at the DFC, with a saturation on performance depending on the specific rule and channel SNR.

We also investigate and study the practical implications of employing distributed MIMO based WSN, especially in the light of the recently proposed decision fusion algorithms for DFC equipped with multiple integrated antennas. A detailed measurement campaign is conducted for an indoor-to-outdoor distributed MIMO scenario with transmit antennas, representing sensors, deployed in a wide variety of indoor environments and receive antennas mounted on top of an outdoor tower, thereby replicating a DFC. Measurements are accumulated both in static and dynamic (people moving around) environments.

For each measurement scenario, large and small scale statistics are derived from the accumulated data, and average values of pathloss and shadowing variations are calculated. Fading distributions derived from the recorded channel impulse responses (CIRs) are found to closely match the double Rayleigh distribution in 21.4% cases, the TWDP distribution in 28.6% cases and the Ricean distribution in 50% cases.

Large and small scale channel parameters calculated from the accumulated measurements are used to model the MAC scenario over which performance of the formulated fusion rules is analyzed for virtual MIMO-based WSN. All the sub-optimal fusion rules, on an average, exploit diversity offered by multiple antennas at the DFC to achieve considerable gain in performance. Among all the rules, CV-ML performs worst and CV-MMSE performs best in all scenarios. MRC, EGC and Max-Log perform in between the two extremes of CV-ML and CV-MMSE. In this case, EGC performs better than MRC and MRC performs better than Max-Log.

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Chapter 12

Queries Processing in Wireless Sensor Network

Kamel Abbassi and Tahar Ezzedine

Abstract

For the super-excellence applications used to control the water level in rivers, temperature handles a very large volume of information and does not stop constantly changing. These spatio-temporal data collected by a network of sensors form a set of thematic, integrated, non-volatile and historical data organized to help decision-making. Usually this process is performed with temporal, spatial and spatiotemporal queries. This in turn increases the execution time of the query load. In the literatures, several techniques have been identified such as materialized views (MV), indexes, fragmentation, scheduling, and buffer management. These techniques do not consider the update of the request load and the modification at the database level. In this chapter, we propose an optimal dynamic selection solution based on indexes and VMs. the solution is optimal when it meets the entire workload with a reasonable response time. The proposed approach supports modification at the database level and at the workload level to ensure the validity of the optimal solution for this the knapsack algorithm was used.

Keywords: wireless sensor network, workload, optimized structure, NP-complete problem, knapsack, materialized view, index, multiple selection problem, monitoring

1. Introduction

A sensor network used to record physical conditions of the environment such as temperature, rainfall, pollution, humidity, wind, etc. These data are sent to a database server which will be processed later.

All this data collected by the sensors will be recorded in a database which is in turn queried by client applications, such as the supervisor, the security agent, or a third-party application.

This database will be queried by complex queries which require resources.

To decrease the response time, it is necessary to use optimization techniques such as materialized views (MV), indexes, fragmentation, and the caching system. All these techniques are proven in the case of relational databases.

A view is a virtual table representing the result of a query on the basis. As the name suggests and unlike a standard view, in a materialized view the data is duplicated.

The index placed on a table will provide quick access to records, depending on the value of one or more fields. In addition, allows to simplify and accelerate the operations of search, sorting, joining or aggregation.

In this work, an approach proposed for the multiple selection of indexes and materialized views with the knapsack algorithm. The work presents an improvement of another approach based on the greedy algorithm. The rest of this work is organized like this: The first section deals with optimization techniques; the problem of multiple selection of indexes and materialized views will be presented in the second section. The contribution to the dynamic workload will be mentioned in Section 4. In Section 5, a discussion of our approach for the case where the database is dynamic will be described. Finally, a discussion on the experiment and the contribution will be discussed.

2. Optimization techniques

The use of optimization techniques is based on two approaches. The first is the sequential use of techniques such as indexes and fragmentations which have depleted physical structure, but the second is the simultaneous use of techniques which have similar physical structure such as materialized views and indexes.

In [1], authors proposed three approaches which are MVFirst, INDFirst and Joint enumeration. But the major drawback of this approach is the sequential and isolating use of these techniques, which does not make it possible to benefit from the advantage of the interactivity between these optimization structures.

The authors say that this last alternative is the best [2]. Bellatrech et al. [3] improve part of the multiple selection problem with storage space management.

The authors use two spies to manage the space shared between two structures, index and VM. If the optimal configuration needs more indexes, then the spy associated with the index will take up space from the VM spy and vice versa.

In [4] use the drop algorithm for the selection simulation of indexes and MV.

These works only deal with the case where the load of requests is static and does not change over time. In [5], authors proposed an approach to dynamically select materialized views. The approach is based on the PRQ predictor to predict the next request and materialize its corresponding views using the conditional probability. This approach uses a cost model based on cloud costs. This work shows a tremendous improvement in terms of cost, execution time, and processing, but the authors only used one optimization framework which is view materialized. Another dynamic approach called Dynamat refreshes the configuration of materialized views if their size exceeds the space allocated for it [6]. Several criteria are used, for example, delete rarely used views. A hybrid approach jointly exploits a static set of persistent views used by multiple request and maintenance sequences, and another dynamic set of aggregated and smaller sizes accessible and replaceable on the fly [7]. However, these approaches focus only on the refresh performance of materialized views and not on query workload. In addition, do not use other optimization structures. Karkad et al. [8] applied the buffer management and scheduling technique to three optimization structures (index, materialized views, and fragmentation). This approach requires caching, planning, and is not dynamic.

In our approach, the simultaneity between materialized and indexed views used to benefit from the interaction between these structures. In addition, a mathematical modulization of the problem has been proposed based on the backpack algorithm which proves their performance compared to the greedy algorithm used by N. Maiz et al. [5].

3. Materialized view and index selection problem

Simultaneous selection of indexes and materialized views is an NP-Hard type problem which gives several optimal solutions [9].

The Knapsack problem, also noted KP, is an optimization problem. Presents a situation which cannot support more than a certain weight, with all or part of a given set $N \in O$ of objects $O = \{o_1, o_2 \ldots \ldots .o_n\}$ each having a weight weight(o_i) and a value $profit(o_i)$. Items put in the backpack must maximize the total value and not exceed the maximum weight S The problem is formalized as follows:

$$\sum_{o_i} weight(o_i) < S \tag{1}$$

$$\forall N \in O, \sum_{o_i \in N} profit(o_i) < \sum_{o_i \in S} profit(o_i) \tag{2}$$

On the other hand, the problem of selecting indexes and materialized views (PSIMV) consists in finding a set of indexes and materialized views constituting the final configuration to optimize the workload requests. This optimization can be in run time and storage space. The Workload requests, index and MV are presented as follows:

$$Q = \{q_1, q_2, \ldots q_m\} \tag{3}$$

$$I = \{i_1, i_2, \ldots i_n\} \tag{4}$$

$$V = \{v_1, v_2, \ldots v_k\} \tag{5}$$

Q presented the Workload queries. This set composed by m queries. I is the set of n indexes and V presented the k materialized views.

S is the size allowed by the administrator to store indexes and MV. Then it is necessary to find a configuration without violating the following constraints:

- Minimize the cost of Workload, i.e.

$$C(Q, Config_{IV}) = Min(C_{IV}(Q)) \tag{6}$$

- The size of the configuration $Config_{IV}$ does not exceed S

$$\sum_{i \in Config_{IV}} size(iv) \leq S \tag{7}$$

The problem of selecting indexes and materialized views is adopted by the genetic algorithm. The starting population is the set of candidate indexes and MVs. The objective function to optimize is the cost of the workload. The next section shows the analogy between the problem of selecting indexes and materialized views and the knapsack algorithm.

3.1 Selection problem with index and MV vs. knapsack algorithm

In this work, we present the correspondence between the problem of the knapsack and that of the multiple selection of indexes and materialized views (**Table 1**).

3.2 Cost model

Typically, the number of indexes and candidate VMs is greater since the input load is significant. The creation of all these indexes and MVs is not possible due to the constraint on the allocated storage space. To solve the problem, we use a cost model which allows us to keep only the most advantageous indexes and MVs. This

Knapsack problem	Problem with selecting indexes and materialized views
Objects	The total set of Indexes and materialized views
Weight	The point shows the size of each object and the required execution time.
Profit	This is the profile to be won if these objects are used. Shows the gain in execution time and storage
Size	The number of bits needed to store the objects that form the optimal solution
Object set	The final configuration of indexes and materialized views

Table 1.
Selection of indexes and materialized vs. knapsack.

model estimates the space in bytes occupied by indexes and VMs, the data access costs and the maintenance cost in terms of number of inputs and outputs.

Indexes and MVs are the objects in this optimization system. Cost of an object is the sum of storage size, access data cost both these indexes and MVs and maintenance cost.

$$Cost_{o_i} = Size_{o_i} + Cost\_Access_{o_i} + Cost\_Mat_{o_i} \tag{8}$$

The benefit provided by an $O_i$object is the difference the cost of the Workload before adding the object *Cost_Load_Before* (O_i) and after the addition of this object *Cost_Load_After* (O_i). the following equation calculates the profit:

$$Profit(O_i) = Cost\_Load\_Before\ (O_i) - Cost\_Load\_After\ (O_i) \tag{9}$$

To add this object to the configuration list, we followed this equation

$$Profit(O_i) = \begin{cases} > 0, & AddO_itoConfig \\ \leq 0, & donothing \end{cases} \tag{10}$$

If $Profit(O_i) > 0$, There is a benefit, so add the object O_i to the configuration, else not add O_i to the configuration.

This query system can be static or dynamic. When the Workload and the data stored in the database are invariable in this case, it is a static system which will be discussed in Section 4. On other hand, if the Workload and the database are modifiable, then it is a dynamic system which will be discussed in Section 5.

4. Statistic workload

A request load is the set of requests that have arrived and are waiting for their turn to be executed. This section will discuss the case where the database does not change, and the requests have arrived successively in random order. Bellatrach et al. [3] proposed a static approach that does not support the changing of Workload. Authors apply the greedy algorithm which does not necessarily provide an optimal solution. In [6], authors show that dynamic programming and more optimal than the Greedy algorithm.

The Knapsack algorithm is an example of dynamic algorithms used for optimization problems. In the proposed approach, Artificial Intelligence uses this algorithm only in the learning phase and afterwards a model will be created to predict the final solution and avoid the execution of this algorithm on each new request.

An optimal configuration is the set of materialized views and indexes which extend to the workload in a reasonable time with the minimum of resources.

The following algorithm takes as input the list of indexes and Materialized views to create an optimal configuration on condition that this configuration extends to the entire load of requests and does not exceed the authorized storage size.

Algorithm 1. Static approach.

```
Input: Index I, MV
Output: Config
Initialization: Config → {Ø}, $Size_{max}$ = 0, $Profit_{max}$ = 0
Start
    O=I   MV
    S=Space authorized by administrator
    for ($O_i \in O$ \{Config} et $Size_{max} < S$) then
        if Profit ($O_i$) > $Profit_{max}$ then
        $Profit_{max} \leftarrow$ Profit ($O_i$)
        Config ← Config {Oi}
        $Size_{max} \leftarrow Size_{max}$ + Size ($O_i$)
        End if
    End for
End
```

S is the size of the disk space allocated to store MVs and indexes, it is fixed by administrator.

Objective function Profit () calculates for each index or MV. It is the difference in cost between the workload run time with or without this object (Index or MV). If this object improves the system, it will be added to the entire configuration. At the end of this algorithm, the final configuration is made up of a set of indexes and MVs which represent the optimal solution. This technique considers the similarity between the two optimization structures index and MV.

These iterations will be repeated until there is no improvement in the Profit () function, or until all indexes and VMs have been selected, or until the limit storage space is exceeded.

Changes at the database level or in the workload require a new configuration to revert to the new Workload. Then you must rebuild new indexes and VMs. This operation is very time consuming.

In Dynamat [8] the authors have removed the least used VMs to free space for new creations. In this approach the authors limit themselves to use only the MV optimization structure.

To solve this inconsistency problem, the authors find three strategies. The first one is that all views are updated regularly at each time interval [10]. The second one is that all views are updated at the end of each transaction [11] and the last strategy is that the changes are propagated in a delayed manner. I.e. a VM is updated only when it is used by a request.

Our approach combines the two structures (Index and Materialized views) to benefit from the structural affinity between these two optimization techniques.

In a real-time survival system, query processing is important. To ensure optimal validation of the solution after the change in workload and database, two artificial intelligence techniques are used.

The arrival of requests is random and varied depending on the context and in this case. On the other hand, the database can be modified during the execution of the queries. In this part we will study the two cases.

We used artificial intelligence to create materialized views for the dynamic processing of the workload and to make requests as visible as possible. With automatic learning, we proposed an algorithm that allows to search for the logical link between the query load and the optimal configuration, then and after the learning phase will predict the final solution (Minimum configuration).

We started with a remodeling phase. Each request is presented by a factor which presents the list of attributes used. on the other side a matrix which presents all the possible solutions which are prepared in advance.

The Workload Q is formed by n queries, i.e., $Q = \{Q_1, \dots Q_n\}$. A query is composed by j attributes, where $\epsilon \ \{a_1, \dots a_k\}$, and each query has the following form: $Q_i = \left\{a^i_j\right\}, \forall i : 1..n, j : 1..k$. The activation function used in this work is presented as follows:

$$f(a_j) = \begin{cases} 1 * a_j & \textit{if } a_j \textit{ used in } Q \\ 0 * a_j & \textit{else} \end{cases} \tag{11}$$

The workload can be presented in form of matrix as follow:

$$MatA = \begin{pmatrix} a^1_1 * f(a_1) & \cdots & a^1_k * f(a_k) \\ \vdots & \ddots & \vdots \\ a^n_1 * f(a_1) & \cdots & a^n_k * f(a_k) \end{pmatrix} \tag{12}$$

A final solution is a set of structures such as Index and MV that guarantees the response to the entire query load with minimal cost. Based on, N attributes, we can find $2^N - 1$ views and the final solution has a view between 1 and $2^N - 1$.

$$FS^f = \left\{v^f_e\right\}, \textit{where } e \in \left(1..2^N - 1\right), f = \left(1..2^{2^N-1} - 1\right) \tag{13}$$

In order to verify if this materialized view v_e is included in the solution FS^f or not, the function $h(v_e)$ having the following form should be used

$$h(v_e) = \begin{cases} 1, & v_e \textit{ if } v_e \textit{ used in } FS \\ 0, & v_e \textit{ else} \end{cases} \tag{14}$$

The maximum number of final solutions is $\left(2^N - 1\right)^{2^N-1}$, where N is the number of attributes in database tables.

The final solutions are presented as follows

$$FS = \begin{pmatrix} v^1_1 * h(v_1) & \cdots & v^{\left(2^N-1\right)^{2^N-1}}_{2^N-1} * h\left(v_{2^N-1}\right) \\ \vdots & \ddots & \vdots \\ v^n_1 * h(v_1) & \cdots & v^{\left(2^N-1\right)^{2^N-1}}_{2^N-1} * h\left(v_{2^N-1}\right) \end{pmatrix} \tag{15}$$

The references of the final solutions are stored in a vector VS with the following form

$$VS = \left\{S_f\right\}, \textit{where} f = \left(1..2^{2^N-1} - 1\right) \tag{16}$$

Figure 1 shows the three layers of our modeling and the steps to create candidate solutions. First step is the extraction of the attributes used in all the tables of the database$\{a_1, .., a_n\}$, then create a vector containing all the possible materialized views, i.e. the possible combinations with the attributes $\{v_1, .., v_{2^n-1}\}$. A materialized view contains at least one attribute and at most all attributes. The number of VMs is $2^n - 1$.

Then the candidate solutions, which presents all the possible combinations of the VMs. The maximum number of solutions is $2^{2^n-1} - 1$.

To apply the automatic learning, To apply machine learning, you have to start with the learning phase, this phase the algorithm will build a logical link between the attributes and the final solutions. The duration of this phase is set by the administrator (**Figure 2**).

The algorithm is composed of two phases: The first phase is used for training. However, the second is used to predict materialized views.

Figure 3 shows the architecture of our approach. The system administrator sets the period for learning the model. If this phase is in progress, each time a new request arrives the system will use the knapsack algorithm to find the right configuration and at the same time prepare the neural network model. At the end of the learning phase the system will use this module provided in the first phase to predict a new optimal configuration for each arrival query.

The final FS solution is the optimal configuration that extends to the workload with a reasonable execution time. With this approach, a logic established between the requests and the final solutions to avoid recalculating each time.

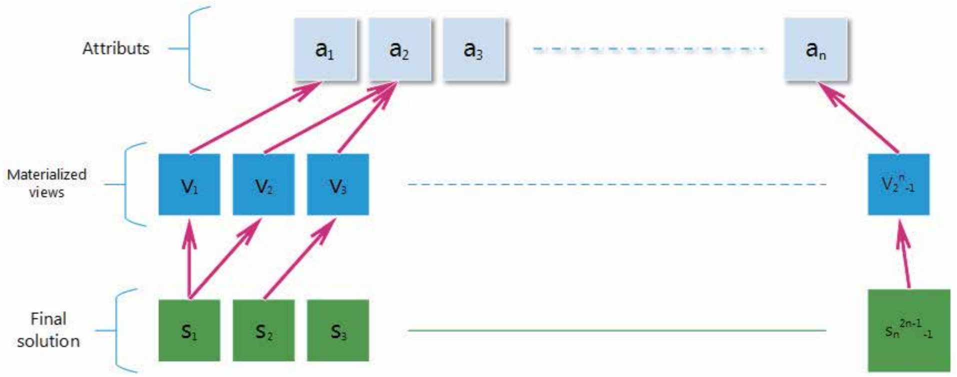

Figure 1.
Final solutions tree.

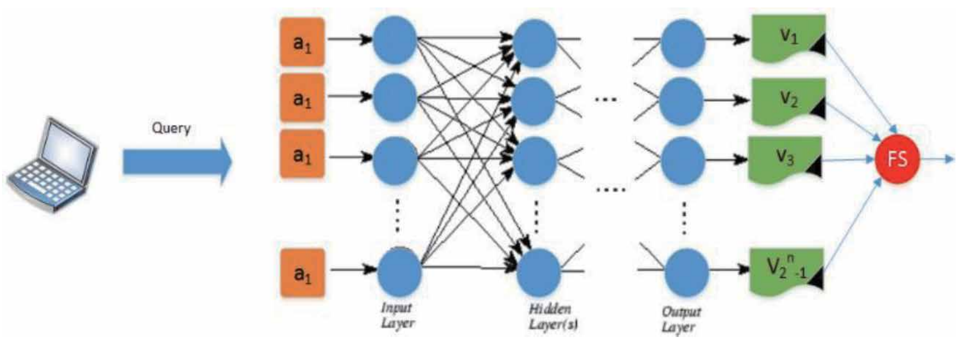

Figure 2.
Machine learning to create optimal solutions.

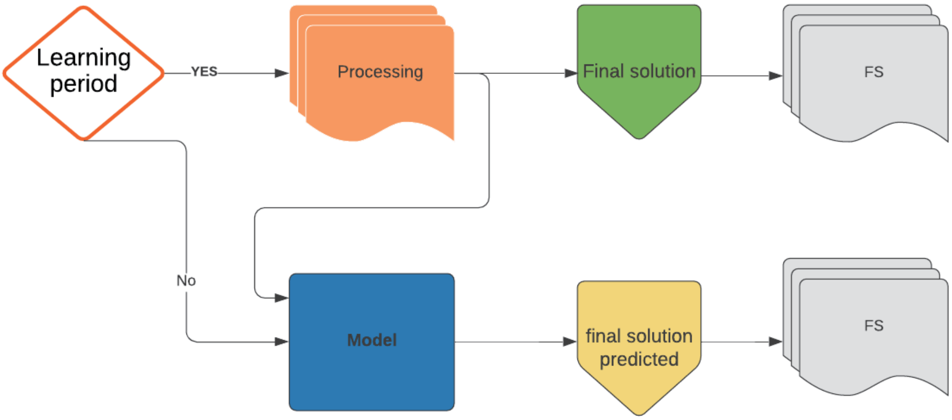

Figure 3.
Switching between the training phase and the prediction phase.

In this experiment uses a workload containing 5 queries numbered from 1 to 5 and a database of 4 attribute differences that make 15 materialized views and 32,768 final solutions (**Table 2**).

Between 09:21 am and 9:47 am the requests arrive randomly. At the start the Workload contains only the query Q5 and for this workload the final solution is 4523 on the other hand the predicted final solution is 25,531 which is our predicted solution is different from the real solution.

To test the approach, an implementation of the algorithm was carried out with Python 3 on a laptop computer equipped with a Windows 10 operating system, 64 bits and 8 GB of RAM. The experimental results are discussed in the following figure.

First, each query is executed with the greedy algorithm to see the final solution as shown by the blue dots in **Figure 4**. In the second step our algorithm will be compared with the first to see if possible, to predict the final solution (orange curve) without wasting the time to recalculate the configuration each time a request arrives.

Time	Query	Workload	Index of final solution	Index of predicted final solution
09:21:00	Q5	Q5	4523	25,531
09:22:00	Q4	Q5Q4	2660	18,747
09:23:00	Q3	Q5Q4Q3	29,366	21,896
09:24:00	Q4	Q5Q4Q3	16,468	24,525
09:25:00	Q5	Q5Q4Q3	29,845	5103
09:26:00	Q2	Q5Q4Q3Q2	3280	23,163
…	…	…	…	…
09:42:00	Q4	Q5Q4Q3Q2Q1	23,181	23,181
09:43:00	Q4	Q5Q4Q3Q2Q1	20,649	20,649
09:44:00	Q1	Q5Q4Q3Q2Q1	8366	8366
09:45:00	Q5	Q5Q4Q3Q2Q1	21,667	21,667
09:46:00	Q2	Q5Q4Q3Q2Q1	4942	4942
09:47:00	Q4	Q5Q4Q3Q2Q1	11,120	11,120

Table 2.
Dataset final solution.

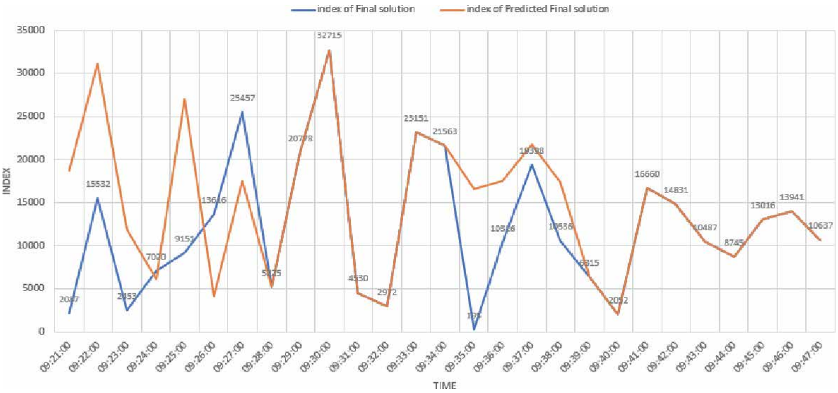

Figure 4.
Final solution vs. predicted final solution.

This figure clearly shows that after a learning phase, the algorithm manages to predict the final solution and consequently a great gain in the execution time and the resources used.

5. Dynamic database

This section discusses the case where the database is dynamic, during the execution of the queries, an update on the data is in progress. Updating all optimization structures is very expensive, so it is a good idea to update only the affected optimization structures.

For this, two binary tables are proposed and stored in the database (**Table 3**). The Matrix IT[i, t] stores the link between the indexes and the tables of the database. If index number 3 is used by table number 5, then IT[3, 5] = 1 otherwise equal to 0. Likewise, for the Matrix VT[v, t] which presents the materialized views linked to the tables. For example, if the materialized view number 5 (MV5) is linked with **Table 4** then VT[5,4] = 1 otherwise equal to 0.

To understand, here is the following example: either Table T1 used by the indexes I1, I2, I4 and MVs V2, V4. Table T3 used by indexes I2, I4 and MVs V1, V4, so each time the database is updated, it is wise to modify only the structure concerned (index or MV). Each time the database tables are updated, a trigger searches for the index or Materialize view affected by this change. More details below (**Figure 5**).

The trigger is an integrated solution in all DBMS. It is a program that launches a series of tasks with each change in the database. It identifies the objects to be modified in the configuration. At each update operation (insertion, update, or

	T1	T1	T3	T4	T5	T6
I1	1	0	0	1	1	0
I2	1	0	1	1	0	1
I3	0	1	0	1	1	1
I4	1	0	1	0	1	1
I5	0	1	0	1	0	1

Table 3.
Matrix IT.

	T1	T1	T3	T4	T5	T6
v1	0	0	1	0	1	0
v2	1	1	0	1	0	1
v3	0	0	0	0	0	0
v4	1	0	1	1	1	0
v5	0	0	0	1	0	1

Table 4.
Matrix VT.

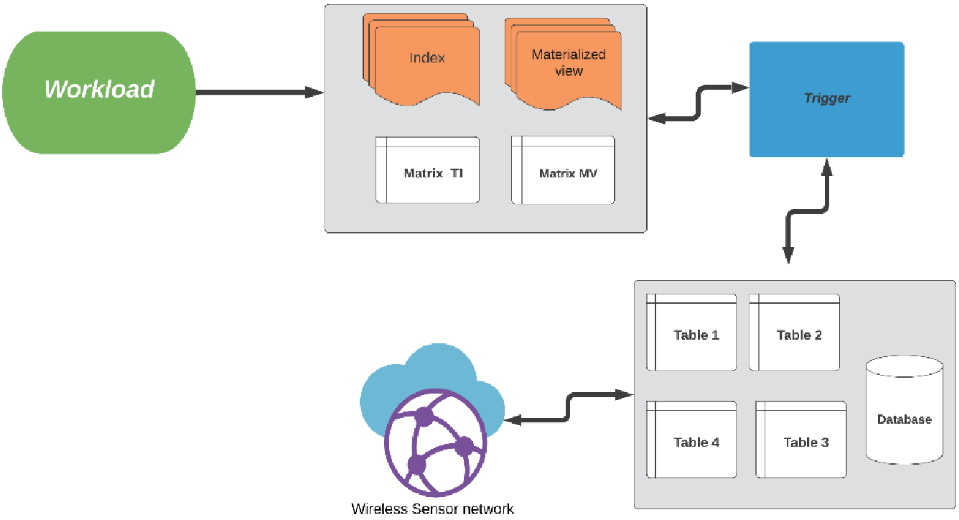

Figure 5.
Algorithm of the dynamic approach.

deletion) the trigger does the same operation on the object concerned (Index or MV). For example, if a new row is inserted in the Table Ti, the trigger inserts the same row in the index and the VM linked by the table Ti. After each iteration, if the size of the configuration exceeds S or if the solution has become non-optimal, Algorithm 1 must be restarted.

This architecture guarantees that all the indexes and MVs form the optimal configuration even after updating the Workload.

Algorithm 2. Dynamic database.

```
Input: Index I, MV, Tables, Workload
Output: Config
Initialization: task→{Ø}, lock=false
Start
    While (true) do
        task←trigger()
        lock←false
        if(task) then
            lock←true
            {I, MV}←get_structure (Tables)
            Update(Config(I,MV))
```

```
            lock←false
        End if
        if(! lock) then
         Execute (Workload)
        End if
    End for
End
```

Algorithm 2 is still running, the ***trigger*** **()** function returns the list of tables infected by update if not returns null. Variable ***lock*** initialized to false to prevent the execution of the workload pending the configuration update. If there are updates, the ***lock*** variable takes true and ***get_structure()*** function searches the structures infected with this modification. This function uses two matrices IT and VT. Then ***Update()*** function modifies the configuration to support the new updates in the tables. And at the end of this operation, the variable lock will be released to execute the Workload.

6. Conclusions

In this work, a similarity between the problem of selecting indexes and materialized views with the Knapsack algorithm was proposed. The contributions are: The first level, the use of the backpack algorithm to present this problem as well as a mathematical modeling, then the use of machine learning to reduce the execution time of the workload. For this, two tables were used to ensure that the optimal configuration remains reliable even after updating the database. To validate this approach, an algorithm developed in python.

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Chapter 13

Interference Mapping in 3D for High-Density Indoor IoT Deployments

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Abstract

Deployment of practical Internet of Things (IoT) in the context of 5G can be hindered by substantial interference and spectrum limitations, especially in the unlicensed frequency bands. Due to the high density of such devices in indoor scenarios, the need for interference characterization which facilitates more effective spectrum utilization is further emphasized. This chapter studies the influence of diverse scenarios for the dense placement of interferers on the spectrum occupancy through the use of 3D interference maps for two popular IoT technologies—LoRa and Wi-Fi. The experiments are performed with software-defined radio (SDR) platforms in real time and an automated positioning tool which provides the measurements to characterize the interference in 3D space. The findings demonstrate a nonuniform character of the interference and the significant impact of fading within the width, height, and length of the examined area. They suggest the role of dynamic relocation for realistic IoT scenarios.

Keywords: 3D interference maps, Internet of Things, sensors, deployment density, spectrum utilization, ultra-dense networks

1. Introduction

Traditional wireless technologies (such as cellular networks) have very limited or no practicality for providing wide area and low-powered communications due to their intensive signal processing and device output power requirements, which would lead to unacceptable energy consumption for the case of Internet of Things (IoT) scenarios. This is the main consideration behind the development of the low-powered wide area network (LPWAN) communication standards such as Sigfox, ZigBee, LoRa, Wi-Fi, etc. Modern IoT technologies show a great potential in the development of agile solutions to novel applications (such as intelligent metering, automated industrial production, home security, and eHealth), which will expand the wireless communications' scope well beyond connected computers, smartphones, and tablets to incorporate a wide range of intelligent appliances and specialized equipment in many areas of human personal and professional life. A recent example is the recognition of the potency of IoT-empowered health care for the efficient treatment of patients, identification of infection clusters, and disease spread prevention during the current, unprecedented COIVD-19 situation [1]. Furthermore, it has been estimated that the number of connected devices is already several times higher than the world's current population [2] and the majority of them will be established through widespread standards such as Wi-Fi, with others such as LoRa also gaining prominence [3]. Despite the technological advances and the variety of technologies and modulation types used, there are a number of challenges that can complicate the operation of the IoT devices running in the Industrial, Scientific, and Medical (ISM) band.

1. Harmonization of ISM bands: in practice, IoT applications are being deployed both in the 868 MHz and 2.4 GHz bands and in those that are not regulated. The ISM range varies for international or national use and it is not harmonized, which may lead to complex interference scenarios [4].

2. Increased demand for radio-frequency spectrum: with increasing number of devices running in ISM bands, the need to provide more operating frequency bands also increases. However, due to the limited availability of free bands, finding free spectrum is a serious challenge. The application of solutions based on cognitive radio and the operation in occupied ISM or unlicensed frequency bands can help meet the growing demand for spectral bands. In this way, the available frequency bands can be used more efficiently and economically.

3. Mutual interference: coexistence of multiple IoT devices in one ISM heterogeneous environment with similar technical specification can cause significant mutual interference. The application of interference coordination approaches can solve this problem. Applying ISM band-specific interference reduction methods can facilitate the harmonious functioning of different heterogeneous ISM devices [5].

The 2.45 GHz ISM band is also interesting because of the ability to flexibly access the radio spectrum, and through the use of cognitive radio methods, problems of interaction between collaborative systems can be avoided. Due to the potential of this ISM band, many cognitive test beds have been developed. There are already many unlicensed devices that use the spectrum in this band in an intelligent manner. But when the spectrum is saturated with more devices, this will result in interference occurrence. In order to assess the feasibility of applying cognitive methods for the use of spectrum, it is necessary to estimate the occupancy in the ISM bands by using long-term monitoring. Due to the huge number of different devices and applications, operating especially in the 2.45 GHz band, differences in the usage of the spectra can be significant and vary considerably even in a small area.

The ever-increasing attractiveness of LPWANs in industrial and research communities is mainly caused by their low energy consumption, low-cost communication characteristics, and long-range communication capabilities. Normally, these networks are able to offer coverage within 10–40 km in rural zones and 1–5 km in urban zones [6]. Furthermore, the LPWANs are tremendously energy efficient, with up to 10 or more years of battery lifetime, and low cost, at around the cost of a single radio chipset [7]. In this context, the features and capabilities of LPWANs have stimulated engineers to realize numerous experimental studies on their performance in outdoor and indoor environments. The up-to-date LPWAN technologies usually use gateways, referred to as concentrators or base stations (BSs), to serve end devices. In this context, the end devices communicate directly with one or more gateways. This is the major difference between traditional WSNs and LPWANs. This type of topology meaningfully simplifies the coverage of large regions, even spanning an entire nation, by taking advantage of the already deployed cellular network infrastructure. Thus, the experiments presented in this chapter are focused on LoRa and Wi-Fi for IoT.

LoRa wide area networks (WANs) are a low-power specification for IoT devices operating in the regional, national, or global networks. It is frequency-agnostic and can use the 433, 868, or 915 MHz bands in the Industrial, Scientific, and Medical (ISM) range, depending on the region in which it is located. LoRa is the physical layer or wireless modulation that is used to implement a long-distance communication link. Data transmission speeds vary from 0.3 to 50 kbps, depending on whether channel aggregation is used. The standard LoRa operates in the 868 MHz (EU)/915 MHz (US) frequency range at a distance of 2–5 km (urban environment) and up to 15 km (suburban), with a transmission speed not higher than 50 kbps. The advantage of the technology is the ability to achieve long-distance connections, with a single base station having the capability to cover hundreds of square kilometers. The size of the covered range is highly dependent on the environment and the presence of obstacles, but LoRaWANs have the best power supply organization when compared to any other standardized communication technology [8].

LoRaWANs employ bidirectional communication by means of a special chirp spread spectrum (CSS) modulation technique, in this way, distributing a narrow band input signal over an expanded channel bandwidth. The signal which results has properties which resemble those of noise, rendering detecting or jamming more difficult. The CSS processing allows increased resistance to both noise and interference [9]. By the same token, however, other technologies operating in the same ISM band may themselves generate interference. Many LoRa parameters such as carrier frequency (CF), spreading factor (SF), bandwidth (BW) and CR can be tuned in order to optimize the performance. The challenges before the implementation of LoRa are related to the implementation of the cognitive network concept, densification and technology coexistence, and interoperability. The maximum duty cycle of devices operating in the ISM bands has a significant influence on the capacity of the network. One of the more important future directions is the integration of cognitive radio into the LoRa standard. In the future, the addition of cognitive radio into the LoRa standard would result in a meaningful reduction in energy consumption. The practical implementation of LPWAN technologies, and exceptionally LoRaWANs, poses challenges for coexistence as the employment of gateways increases in urban regions. It is essential to devise coordination mechanisms between gateways from the same or different operators to limit interference and collisions. The coexistence mechanisms include coordination and reconfiguration protocols for gateways and end devices. The high attractiveness of LPWANs gives rise to a new challenge called technology coexistence. Many autonomous networks will be implemented in close proximity and the interference between them must be controlled in order to keep them in operational state. Nowadays, LPWANs are not designed to handle this forthcoming challenge that will cause the spectrum becoming overly crowded. Coexistence management for Wi-Fi and Bluetooth will not operate well in the context of LPWANs' deployment. Due to their large coverage areas, LPWAN devices can be subject to an exceptional number of hidden terminals. Enabling different technologies to coexist on the same spectrum is very challenging, mainly due to different entities maintaining different technologies [10].

There are a number of IoT usage scenarios and solutions which utilize the Wi-Fi standard. User identification and authentication is important for robust access to smart home appliances and specific usage data collection and processing (for example eHealth monitoring and access control to various appliances depending on the physiological and behavioral traits of the different members of the household) [11]. Using Deep Learning, this can be achieved without separate dedicated devices via the channel state information (CSI) extracted from the Wi-Fi signals that are transmitted by the IoT devices during their operation as they are reflected in different manners from users of diverse categories (defined by their age, body shape, and daily routine). Interoperability between Wi-Fi-based IoT and other widespread wireless standards is another significant issue in literature. For example, in agricultural automation, these devices have to operate together with Bluetooth and radio-frequency identification (RFID) instruments. Their coexistence in the Industrial, Scientific, and Medical (ISM) band can be facilitated via rigorous analysis and adaptive frequency hopping [12]. Another aspect of interoperability is addressed for the case of operation between IoT and traditional wireless devices within the 2.4 GHz band due to the different characters of their dataflows. The IoT appliances with their acute battery limitations require low-latency and energy-efficient communications which may be complicated by the bandwidth-intensive transmissions of computers and smartphones. A solution to this issue is implementing an adaptive admission control for the IoT flows, which considers the wireless channel's characteristics [13]. Alternatively, this kind of interoperability is addressed via a Wi-Fi physical layer modification which utilizes multi-antenna access point (AP) [14] or traffic differentiation between IoT and traditional communications through advanced packet scheduling [15].

Scientific efforts are made to solve the present and future issues (mainly in terms to their dependability [16, 17]) with their practical deployment in 5G and beyond networks. Many of them have been focused on multiple wireless standards' coexistence in the license-free spectrum [18], interference mitigation, and coverage extension in the urban environment from the point of view of the overall access networks [6, 19, 20] or controlled retransmission of messages to increase the QoS by avoiding collisions [21]. Such approaches will need to be supplemented by a characterization of spectrum usage, which facilitates utilization analysis and implementation of dynamic access to the shared frequency resource via cognitive radio (CR)-enabled devices. In the ISM bands which are already heavily congested by traditional communications, the necessity of such software-defined monitoring is even more present. Furthermore, spectrum utilization is very different in indoor and outdoor scenarios, which requires that they should be analyzed separately [22]. Based on these observations, the importance of IoT's interoperability in indoor environments is established, and thus, the necessity for interference analysis is emphasized.

The experiments presented in this chapter examine and evaluate the spectrum occupancy and interference of dense indoor scenario for LoRa and Wi-Fi. Multiple interferers for each of these two standards are implemented using the hardware platform PlutoSDR by Analog Devices to develop the high deployment density scenarios expected in 5G, where substantial levels of mutual interference are almost inevitable. Their influence on the spectrum occupancy is shown through 3D interference maps built using an automated testbench, which collects the received signal strength measurements at each location in the examined area for six deployment scenarios in which the number of active interferers and the density of their placement are varied. Thus, this chapter presents the following contributions:

- 3D heatmaps for different deployment densities and locations of interferers in LoRa and Wi-Fi standards.

- Exemplifies the limitation of IoT devices' density and interference avoidance as the number of interferers increases.

- Exemplifies the effect of fading for localization of interference-free areas.

The rest of this chapter is organized as follows. Section 2 describes the experimental setup, the measurement collection system, the hardware and software tools used, and the procedure for data processing. Section 3 illustrates the results, while the conclusions and directions for future work are given in Section 4.

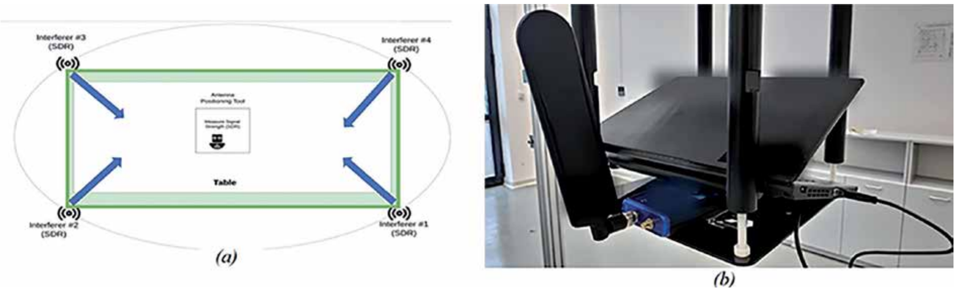
2. Experimental scenarios and data processing

2.1 Experimental setup

The setup for the experiments is shown in **Figure 1**, and it encompasses an area with dimensions of [6000 x 2000 x 800] mm, which is the scope of coverage of the automated positioning system (APS). The APS utilizes a mechanical automated positioning tool (APT, marked with a yellow rectangle in **Figure 2**), which moves along a route preliminary programmed via the computer operating the APS. This route is within the width, length, and height of the aforementioned dimensions, that is, restricted by the four columns, as shown in **Figure 2**. A laptop computer controlling the PlutoSDR receiver which collects the measurements is mounted on the APT (**Figure 1**). The APS covers a plane with dimensions of [6000 x 2000] mm at each of these four elevation levels—0, 250, 500, and 750 mm. They form the 3D axis along which the APT moves. The 3D interference map is produced from the measurements by cubic interpolation.

Four PlutoSDR transmitters which play the role of interferers for other potential IoT nodes in both the LoRa and Wi-Fi standards are shown in **Figures 1** and **2**. They are placed at the four corners of the area's periphery (**Figure 1**; they are also marked with red rectangles in **Figure 2**). Thus, six scenarios for the interferers' density and spectrum occupancy are formed for each of the two wireless standards. Their description is outlined in **Table 1**. In the first four scenarios, the interferers are placed in the periphery, 2 m from the edge of the table which is situated in the middle of the experimental setup. In each of these scenarios, the spectrum occupancy is assessed depending on the number of active interferers. For the other two, all four transmitters are active but they are moved closer to the table—by 1 m for the middle position (S5) and by 2 m, that is, the interferers are placed on the four edges of the table for closest positions (S6).

All interferers have a transmission power of −3 dBm (PlutoSDR has an output power of 7 dBm and a 10 dB attenuation setting is applied [23]). The transmitters as well as the receivers are implemented using the GNU Radio software package [24], while the periods of transmission, reception, and measurement are managed via a Python script. The operational parameters of the SDR nodes are described in **Table 2**.



(a) *(b)*

Figure 1.
Experimental setup and APT with (a) PlutoSDR and (b) its host computer.

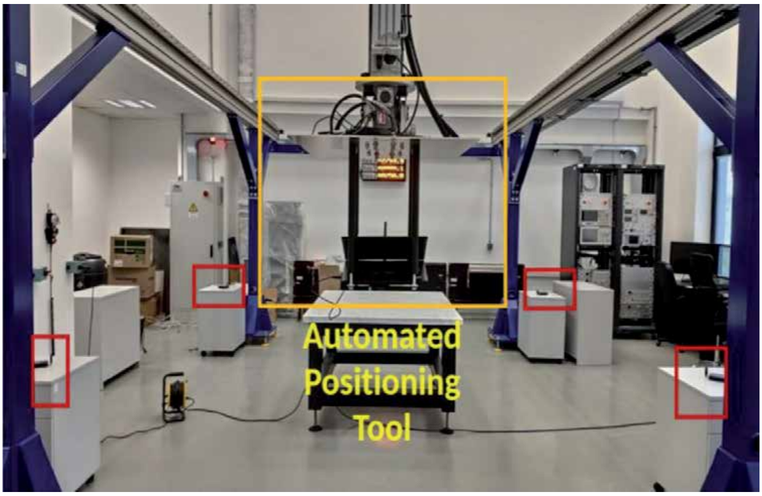


Figure 2.
APS and APT.

	Scenario description	Active transmitters
S1	One interferer	#1
S2	Two interferers	#1 and #3
S3	Three interferers	#1, #2, and #3
S4	Four interferers (farthest position)	#1, #2, #3, and #4
S5	Four interferers (middle position)	#1, #2, #3, and #4
S6	Four interferers (closest position)	#1, #2, #3, and #4

Table 1.
Deployment scenarios.

Parameter	Value
Center frequency	868 MHz (LoRa)/2.484 GHz (Wi-Fi)
Bandwidth	125 kHz (LoRa)/5 MHz (Wi-Fi)
Antenna gain	2 dBi (LoRa)/4 dBi (Wi-Fi)
Transmission power	−3 dBm

Table 2.
Operational parameters.

The APS collects the measurement samples by moving along the [6000 x 2000] mm plane for each of the four heights with a step of 1000 mm in the x-coordinate (i.e., the length) and 200 mm in the y-coordinate (width), as underlined in **Figure 3**. As a result, each plane contains 77 measuring points (marked with ×). At each point, the APS performs one measurement over a period of 7 s. After covering all points of the current plane, the APT is elevated by 250 mm and the process is repeated for each of the four heights (0, 250, 500, and 750 mm in the z-coordinate).

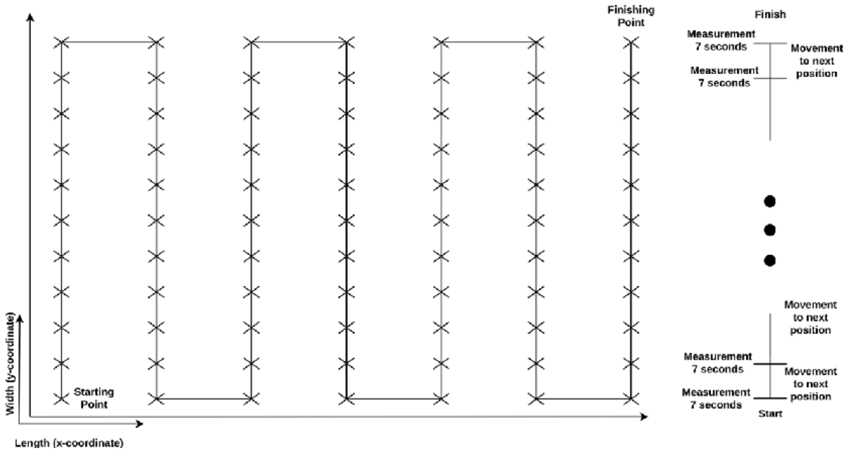


Figure 3.
A schematic of the measurement path for a single plane.

2.2 Data processing

To construct the 3D interference maps, the measured signal batches at each measurement point need to be filtered out so that only the samples with the strongest amplitude remain. Thus, their mean which characterizes the signal strength at this point will be maximized. The filtering is performed on the basis of energy detection spectrum sensing in the following way. For each 256 samples in the signal batch, their mean is compared against a constant decision threshold that is predetermined based on the highest instantaneous amplitude shown in the time domain representation of the batch. The higher the threshold's value is, the fewer samples will be produced in the resulting signal after the filtration. A minimal number of samples is chosen (at least a few hundred, usually in CR studies, over a few thousand [25], 30,000 in this case). If the threshold is too high for at least that number of samples to be produced, it is lowered by 2.5%. This coefficient is determined empirically as a viable compromise between the resulting number of samples and the speed of the process (a smaller reduction decreases the speed but will lead to limiting the signal samples to those which will amount to the highest mean).

3. 3D interference maps

The mean value of the filtered signal determines the power of the received interference power at each measurement point. In each of the six scenarios, a 3D interference map is constructed for both the Wi-Fi and LoRa standards via cubic interpolation of the received interference power means of the 77 measurement points at each of the four elevation levels (0, 250, 500, and 750 mm) in a separate plane. These planes describe the 2D interference distributions (illustrated with the color map) at each height, while together they represent the interference in 3D.

The interference maps for LoRa and Wi-Fi for the six scenarios are illustrated in **Figures 4**–**13**. To examine more closely some sections of the maps' layers which are partly obstructed by higher planes (i.e., the y-coordinate interval of [0; 1000] mm), they are represented as 3D bar plots. Such graphics are included for Scenarios **S1** and **S6** for LoRa (**Figures 5** and **8**) and **S3** and **S5** for Wi-Fi (**Figures 11** and **13**)

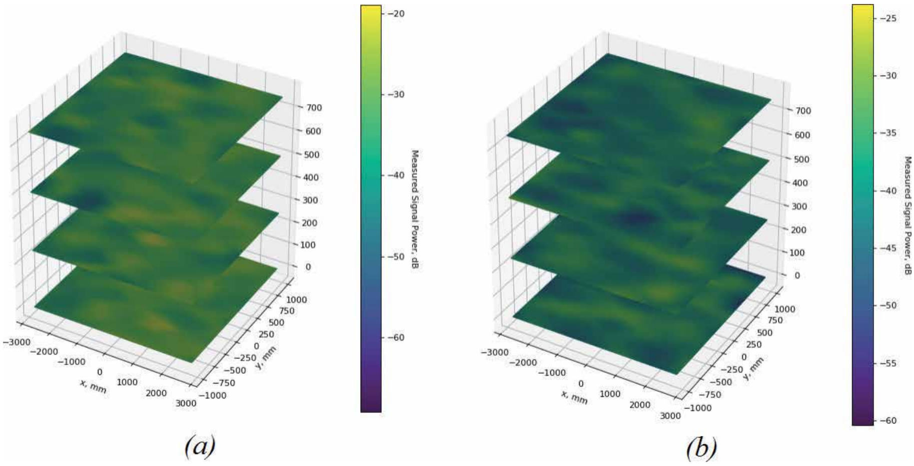


Figure 4.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S1** *(one active transmitter).*

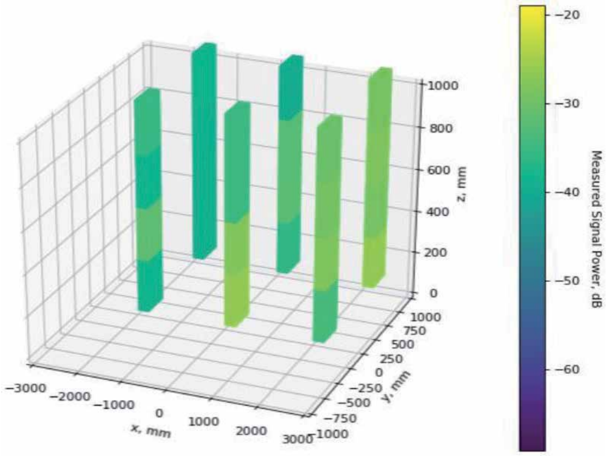


Figure 5.
3D bar plot for the LoRa sensor, z = [0, 250, 500, 750] and x = [−2000, −0, 2000], Scenario **S1**.

because they provide significant information for weak-signal spots which are not clearly seen in the complete 3D interference maps. **Table 3** outlines the coordinates (in x- and y-axes) at which the signal power bars are shown.

Starting with the first four scenarios, the spectrum occupancy is examined with the increase of the number of transmitters. For LoRa, it is clear that a significant portion of the area is permeated with strong signals even for a single active interferer. There is, however, some dissipation with height which creates sections with low interference power (spectrum holes) where communication may be feasible, especially on the opposite end of the area as seen from **Figure 5**. They are also present, even though much more limited, for the second scenario (**Figure 6**) and are localized away from the active interferers (#1 and #3, situated on bottom-right and top-left corners of **Figure 1**, respectively). As the number of emitters is increased, sections with very high interference power are only broadened (**Figures 7** and **9**).

For the other two scenarios which bring the four active interferers closer to each other (**Figures 10** and **12**), no significant difference in the power intensity is observed. Nevertheless, the sections with the highest interference concentration

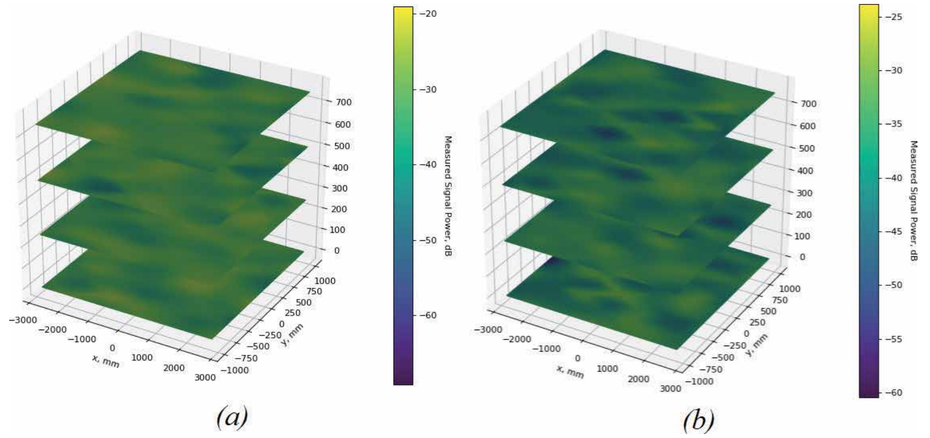


Figure 6.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S2** *(two active transmitters).*

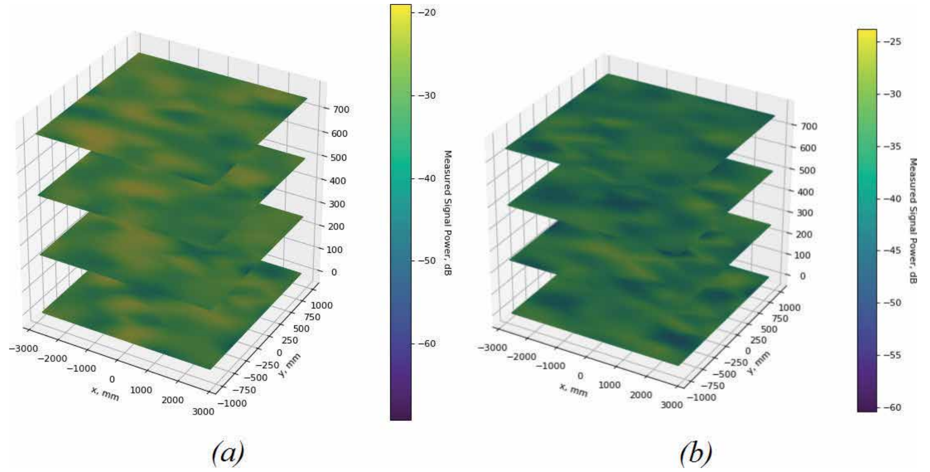


Figure 7.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S3** *(three active transmitters).*

shift from the table's center to the sides. The only spectrum holes are present in the center of Scenario **S6** (**Figures 12** and **13**) at height z = 0 mm. However, they are very limited by the surrounding interference regions and are thus, hardly viable for the placement of communication nodes.

The same scenarios are illustrated for the Wi-Fi standard (**Figures 4–12**). They present more interesting results due to the higher carrier frequency, compared to LoRa. The strongest interference power is generally measured close to the transmitter, nevertheless, this does not hold for every scenario as is seen in **Figures 7** and **9**. Additionally, it is observed that the interfering signals dissipate more intensively in the higher elevation levels (500 and 750 mm) so that the sections with the highest power are shrinking while the medium (yellow/light green) and low (dark green/violet) regions are expanding (**Figure 8**). Thus, the increase in fading with distance both on the same plane but also with height in 3D is a significant factor in the 2.4 GHz ISM band. The interference sources' influence can be substantially diminished if their height is varied. As a consequence, drone-based and other mobile IoT devices can benefit from their abilities for repositioning in 3D.

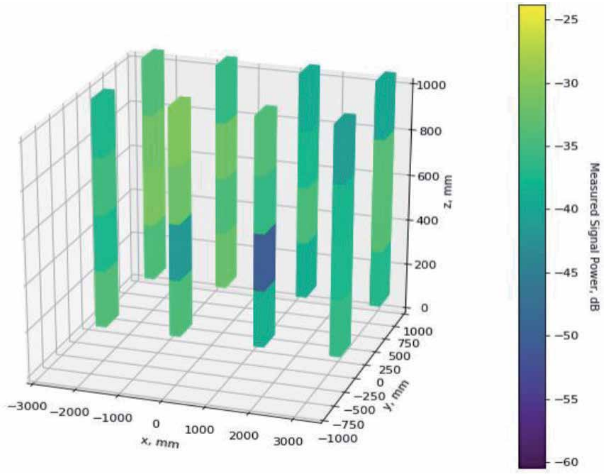
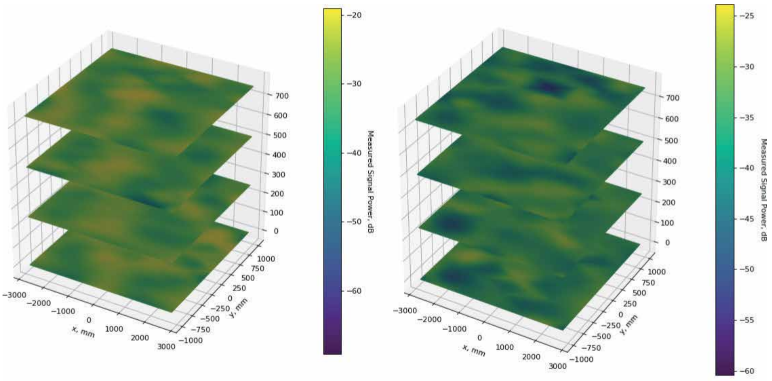
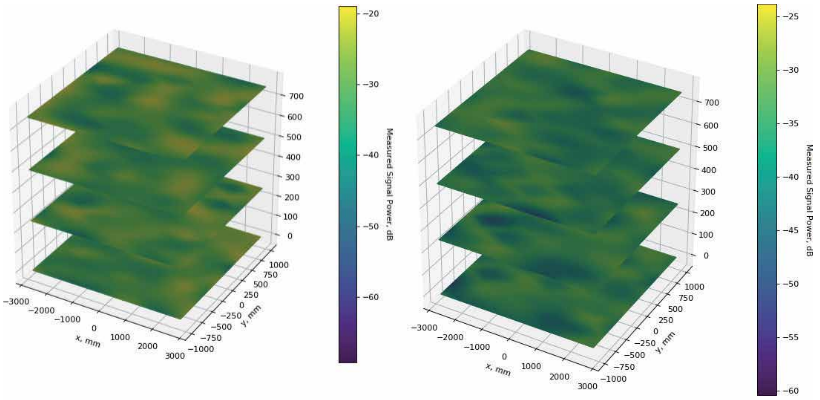


Figure 8.
3D bar plot for the Wi-Fi sensor standard, z = [0, 250, 500, 750] and x = [−2800, −1000, 1000, 2800], scenario **S3**.



(a) (b)

Figure 9.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S4** *(four active transmitters, farthest position).*



(a) (b)

Figure 10.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S5** *(four active transmitters, middle position).*

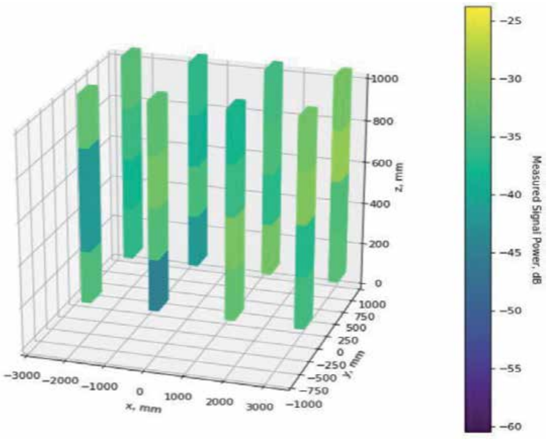


Figure 11.
3D bar plot for the Wi-Fi sensor standard, z = [0, 250, 500, 750] and x = [−2800, −1000, 1000, 2800], scenario **S5**.

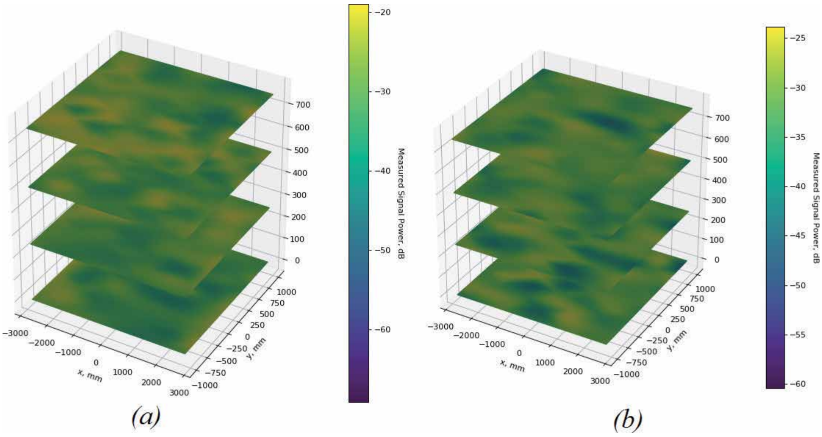


Figure 12.
3D interference map for (a) 868 MHz (LoRa) and (b) 2.484 GHz (Wi-Fi) for z = [0, 250, 500, 750], scenario **S6** *(four active transmitters, closest position).*

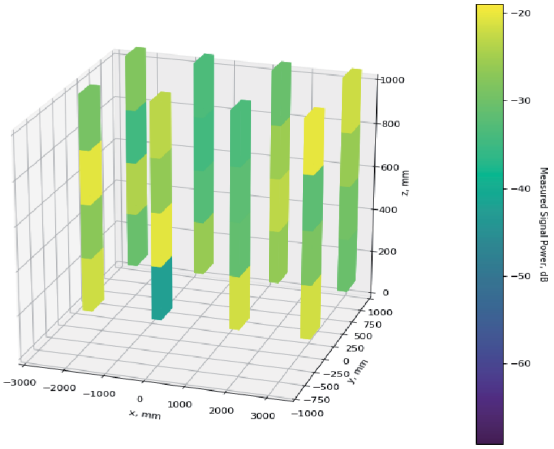


Figure 13.
3D bar plot for the LoRa sensor standard, z = [0, 250, 500, 750] and x = [−2800, −1000, 1000, 2800], scenario **S6**.

Figures	Value (mm)
6	[-2000, 0], [-2000, 1000], [0, 0], [0, 1000], [2000, 0], [2000, 1000]
9, 12, and 14	[-2800, 0], [-2800, 1000], [-1000, 0], [-1000, 1000], [1000, 0], [1000, 1000], [2800, 0], [2800, 1000]

Table 3.
Coordinates in x- and y-axes.

When it comes to scenarios **S5** and **S6**, there is some noticeable change in the interference distribution (**Figures 10–12**), as the spectrum holes shift to the table's center. At the same time, the interference power has increased substantially, mainly in the observed area's periphery. Thus, when the interferers are within a very short distance between each other, it is much more difficult to diminish their influence, even in the higher levels of elevation.

4. Conclusion

This chapter presents a spectrum occupancy evaluation for two popular IoT communication standards, LoRa and Wi-Fi, based on extensive experiments. These include the change of the interfering nodes' number and their location in dense indoor placement. The implementation is realized using the PlutoSDR hardware platform. The 3D interference maps show that the effect of fading with distance on the same plane and in height is crucial in localizing interference-free areas in dense deployments where even with the wireless standards' mechanisms for multiple accesses, it is likely that some nodes and/or malicious users will create in-band interference. In the case of LoRa in the 868 MHz band, interference is a much more substantial issue, regardless of the interferers' number and proximity. As for Wi-Fi sensors, due to the much higher carrier frequency, the interference's influence may be reduced substantially even within the span of a couple of meters. Thus, algorithms for adaptive repositioning in 3D have the potential for improving the communications of indoor IoT networks, aside from or in concurrency with future dynamic access techniques such as volumetric spectrum sensing [26]. Such methods can also be extended with Deep Learning-based node identification for protection against physical layer attacks [27].

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Chapter 14

Applications of Prediction Approaches in Wireless Sensor Networks

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Jamal-Deen Abdulai and Ferdinand Apietu Katsriku

Abstract

Wireless Sensor Networks (WSNs) collect data and continuously monitor ambient data such as temperature, humidity and light. The continuous data transmission of energy constrained sensor nodes is a challenge to the lifetime and performance of WSNs. The type of deployment environment is also and the network topology also contributes to the depletion of nodes which threatens the lifetime and the also the performance of the network. To overcome these challenges, a number of approaches have been proposed and implemented. Of these approaches are routing, clustering, prediction, and duty cycling. Prediction approaches may be used to schedule the sleep periods of nodes to improve the lifetime. The chapter discusses WSN deployment environment, energy conservation techniques, mobility in WSN, prediction approaches and their applications in scheduling the sleep/wake-up periods of sensor nodes.

Keywords: prediction models, wireless sensor networks, time series models

1. Introduction

Wireless Sensor Networks (WSNs) is made up of sensor nodes that are capable of sensing environmental phenomena and cooperatively transferring the sensed data to a base station without the use of wires. The sensor nodes are spatially distributed in their deployable environment to observe some phenomena within their immediate neighborhood. They can be deployed in the tens, hundreds or thousands depending on the application requirements. These sensor nodes are smart devices and may monitor environments such as homes, inventory, transportation, traffic situation, health of humans, structural health, track animals, air quality, water quality, military, and may even serve as surveillance systems [1]. Over the years, WSNs is gradually becoming the technology of choice for industrial applications and research, for environmental monitoring (EM) applications considering the number of advantages that comes with its use [2, 3]. For example, a WSN is resilient (i.e., adaptive to node failures), scalable (i.e., easy to add nodes to the network), robust (i.e., can withstand harsh environmental conditions), flexible to setup and deploy, cheap, and the network requires no infrastructure [4]. Despite the large number of advantages, WSNs are challenged with a number of issues. These include but are not limited to communication, memory size, energy, processing capacity, and security [5].

2. Types of deployment environments

Wireless Sensor Networks may be classified according to the deployment environment. **Figure 1** shows the classification of WSN according to the deployment environment. WSNs may be classified according to the type and environment of the data being acquired. The sensor nodes may either be deployed terrestrially, that is either aboveground or underground. They may be underwater or multimedia (when deployed to capture videos, images, and audios) or simply numeric data.

WSNs have also been classified according to their mobility, mobile (when the sensor nodes move in their deployment environment) and stationary [6]. In both underground and underwater wireless sensor networks (**Figure 1**), the sensor nodes are buried either in the soil or placed underwater to measure the condition of their respective environments. The buried sensor nodes communicate with a sink above ground and send data through it to a monitoring station [7].

2.1 Wireless underground sensor networks (WUSN)

Wireless Underground Sensor Networks (WUSNs) as shown in **Figure 2** is a well-studied area [4]. They are used in different applications which include intelligent agriculture, power grid maintenance, pipeline fault diagnosis, etc. [8, 9].

Compared with traditional terrestrial Wireless Sensor Networks, WUSNs suffer special communication challenges characterized by the weak signal propagation in soil, rocks and other underground materials. Underground signal propagation is challenged with strong attenuation and signal losses [7]. Traditionally, WUSNs use electromagnetic (EM) waves to establish connection among transceivers underground. However, EM waves have several shortcomings; antenna sizes, short communication range, and the channel conditions are highly unreliable. There are new techniques such as magnetic induction (MI) that have the potential to overcome the challenges posed by the use of EM waves in WUSNs. Underground sensors are equipped with batteries which are difficult to charge or replace when the sensor nodes energy are depleted. Conserving underground sensor nodes' energy is crucial to extending the lifetime of the network and to achieving optimal performance.

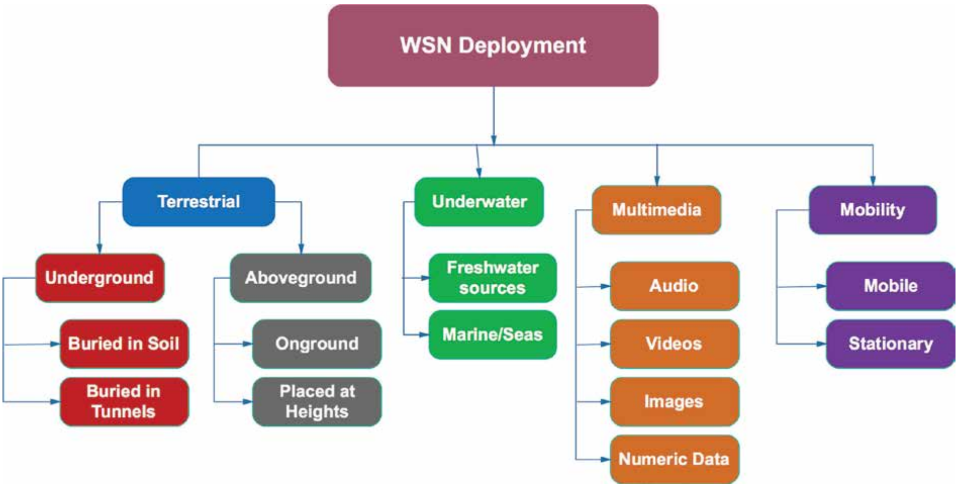

Figure 1.
WSN deployment types.

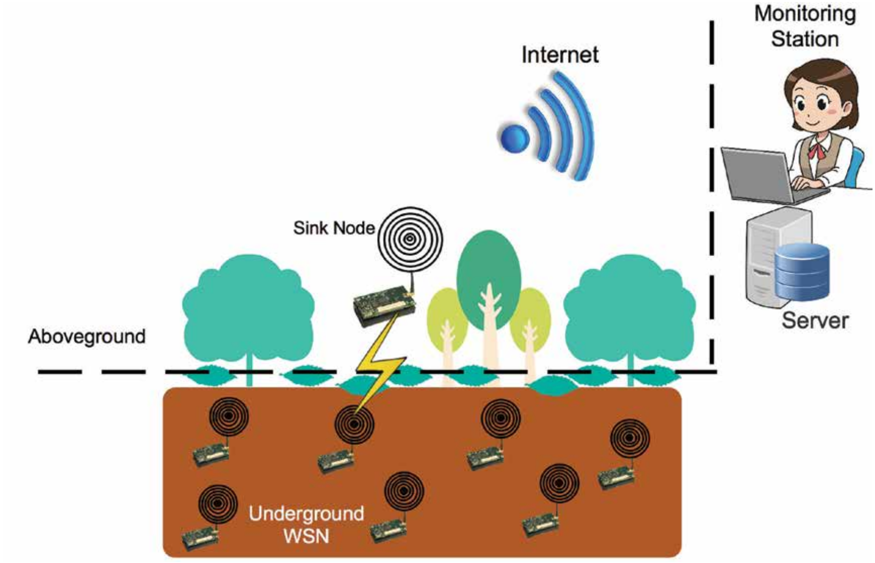

Figure 2.
Underground deployment.

2.2 Wireless underwater sensor networks

Wireless Underwater Sensor Networks (**Figure 2**) is an area that has caught the attention of researchers in recent times [10, 11]. Underwater Sensor Networks are useful due to their several implementation areas which include marine pollution monitoring, marine data gathering, tsunami detection, threat detection at seaports, and underwater telemetry.

The monitoring is usually performed using navigation assistance such as autonomous underwater vehicles (AUV) and vehicle surveillance. Wireless Underwater Sensor Networks (e.g., marine monitoring) suffer from limited bandwidth, node failures due to harsh environmental conditions, signal fading, and propagation delay [12].

Underwater sensor nodes normally communicate using acoustic waves to a surface buoy or sink above the water. It is also possible to employ non-acoustic communication techniques such as radio frequency (RF), magnetic induction (MI), and underwater free-space optics in underwater sensor networks [13].

The dynamic nature of the water environment is related to the content salt, and its turbidity. Hence, the communication channel also becomes dynamic. RF signals, when exposed to these environmental characteristics, suffer high attenuation. Magnetic Induction may also be used for underwater propagation but requires the use of large-sized antennas which is somewhat impractical in such environments. Acoustic communication is the preferred method for underwater communication since acoustic waves suffer less attenuation and are able to travel long distances due to their low frequencies. Nodes that are connected using acoustic waves constitute underwater acoustic sensor networks (UASNs). UASN nodes are energy hungry nodes which consume a great deal of power compared to sensor nodes deployed to monitor environmental conditions on land. There are several techniques discussed in the literature to overcome the energy problem in UASN and to minimize the energy consumed by the UASN to improve on the network lifetime. Energy efficient routing protocols and clustering protocols are two such techniques adopted to minimize the energy consumed by sensor nodes deployed in WUSNs and UASNs [13]. Current existing routing protocols are group into receiver-based and sender-based which are further categorized based on energy, geographic information, and hybrid routing protocols [10].

An Energy Optimized Path Unaware Layered Routing Protocol (E-PULRP) that minimizes the energy consumed in a dense 3D-WUSN is described in [14] as a typical example of an energy-based routing protocol. E-PULRP uses on the fly routing to report events to a stationary sink node.

E-PULRP has two phases: layering and communication. Nodes occupy layers in a concentric shell around the sink node in the layer phase. The nodes within one layer have the same number of hop counts to the sink node. The E-PULRP protocol is designed to follow a network model in which the total volume in the area of interest is subdivided into small-sized cubes with a binomial probability distribution for a node occupancy. The protocol assumes that the number of cubes is large. Following Poisson approximation to the binomial distribution, we can calculate the probability of k nodes occupying a volume V as:

$$Pr\left[x=k\right]=\frac{(\int v\rho dv)^{k}}{k!}exp-\int v\rho dv \qquad (1)$$

where:

ρ = is the volume density of the sensor nodes.

$\int v$ = indicates integral over the volume V.

Physical properties such as temperature and chemical properties affect underwater communication. Another key factor that affects underwater communication is the depth of transceivers. In E-PULRP, for a transmitted energy of $E_{\mathrm{T},}$ the received energy E_{R} at distance R, is modeled as follows:

$$E_R=\frac{E_T}{R^{(B/10)}10^{(\alpha R+\beta)/10}} \qquad (2)$$

where:

B = takes values 10, 15 or 20 depending on the type of propagation.

α = is a range-independent absorption coefficient.

β = is a constant independent of range.

E_{T} = the transmitted energy.

E_{R} = the received energy/power of the control packet.

In this layering phase, the protocol allows communication to occur only when energy levels of layers close to the sink are chosen. Concentric circles are formed around the central sink and the structure ensures packet forwarding towards the central sink. The layers in this phase are formed as follows: 1) Layer 0 initiates a probe of energy; 2) Nodes with energy equal to the detection threshold (E_{D}) assign layer 1 to themselves; 3) The nodes in layer 1 communicates with the sink using a single hop and 4) waits for time *k* to transmits a probe with energy to create layer 2 (i.e., made of nodes in layer 1 with energy equal to E_{D}.

The detection threshold, (E_{D}) and the waiting time *k* are calculated as follows:

$$E_D=\frac{E_{pl}}{\alpha_l^{(B+10)}10^{(\alpha\alpha_l+\beta)/10}} \qquad (3)$$

where

E_{pl} = the probing energy

$$l=thelayer$$

$$k=\frac{\lambda_{\min}\left(E_R-E_D\right)}{\gamma} \qquad (4)$$

γ = energy dependent factor which is the ratio of the energy remaining in the node to the total initial energy

$\lambda_{\min}$ = constant.

In the communication phase, intermediate relay nodes are selected to send packets to the sink using multiple hop routing path to determine nodes *on the fly*. In this phase, nodes at the lower layers nearer to the source node are first identified as potential forwarding relay nodes. For example, if a source node, S in layer l sends a control packet, a node, N in the network who receives this control packet may declare itself as a potential forwarding node. This self-declared potential node waits at a time period given in Eq. (4) to listen if any other node has not declared itself as a relay node. It does this by comparing its signal strength Received Signal Strength Indication (RSSI) with other nodes' RSSI.

Once its RSSI value is less than all others, then it forwards the data packet, otherwise it will go into silent mode. A classic example of a cluster-based energy efficient UWSN is SEEC: Sparsity-aware energy efficient clustering protocol for underwater wireless sensor networks. SEEC was proposed by [15] to search sparse regions in the network. The network is divided into subregions of equal sizes. With the use of sparsity search algorithm (SSA) and density search algorithm (DSA), sparse and dense regions in the network. The lifetime of the network is improved through sink mobility in the sparse regions and through clustering in the dense regions. SEEC minimizes the energy consumed in the overall network by balancing the two sparsity search algorithm (SSA) and density search algorithm (DSA).

In SEEC, random nodes are deployed underwater and the network formed is divided into 10 regions. The position of each node in the network is dynamic due the dynamic nature of the deployable environment. The 10 regions are created to determine the sparse and dense regions. SEEC employs three sinks (i.e., a static sink at the top of central point of the sensor network field and two mobile sinks positioned at the sparse regions). Each sensor nodes coordinate is first determined in order to know its current region in the network field (i.e., sparse or dense).

A simple algorithm that checks the number of nodes in a region is used to determine a sparse or a dense region. If the number of nodes is minimum, then then node is in a sparse region other the node is considered to be in a dense region. When the searching is completed, then the nodes in the dense region are placed into clusters. To conserve energy and increase the lifetime of the network, SEEC is designed to cluster the top four (4) densely populated regions. Nodes in a dense region collaborate to select their cluster head (CH). The CH is the node with low depth and high residual energy.

$$E_{ave} = \frac{Total\,Residual\,Energy}{Number\,of\;Alive\,Nodes}$$

$$rand\,Th \tag{5}$$

$$Th(i) = \frac{p}{1 - p\left(mod\left(r, \frac{1}{p}\right)\right)}$$

2.3 Wireless multimedia sensor networks (WMSNs)

Another type of WSN is the Wireless Multimedia Sensor Networks (WMSNs). These types of sensor networks are designed to monitor multimedia events and are capable of retrieving images, videos, audios, and scalar wireless sensor data. WMSNs come with additional challenges on top of the challenges of traditional WSNs. WMSN challenges include real-time delivery, high bandwidth demand, security, tolerable end-to-end delay, coverage, and proper jitter and frame loss rate [16]. Video streaming requires high bandwidth for it to be delivered. Streaming at high date rate also means that more energy will be consumed.

Several approaches have been proposed to also reduce the amount of energy consumed for delivering the content. Current studies have looked into the design of energy efficient MAC and routing layer protocols that are capable of handling low data rates [17, 18]. Also, to overcome the other challenges apart from the amount of energy utilized during content capturing and delivery, new approaches have been proposed in WMSNs to ensure data sharing security, quality of service assurance in providing real-time multimedia data and to ensure algorithms are designed to compress the images, videos, and audios before transmission to reduce the amount of energy consumed for such operations [19].

2.4 Mobile wireless sensor networks (MWSNs)

There are some application domains that static wireless sensors may not be a good option to deploy, hence, the introduction of Mobile Wireless Sensor Networks (MWSNs). Mobile sensors are capable of moving freely in their environment. This type of WSNs are good for deployments that require maximum coverage to monitor the physical environmental conditions since the mobile nodes can spread out when gathering information and reposition themselves. Mobile sensors improve coverage, energy efficiency, and channel usage [12]. In the last decade, studies into MWSNs have focused on sensor node coverage, energy efficiency, sensor relocation and deployment [20]. Following the studies conducted, the energy efficiency schemes discussed in this area is of key interest. There are two main approaches of improving the energy efficiency in MWSNs: reducing the energy consumption and harvesting energy to power sensor nodes.

2.5 WSN topologies

The arrangement of wireless sensor nodes in a Wireless Sensor Network is critical for maximizing the network lifetime. The network topology adopted in a deployment environment affects factors such as network connectivity. Network connectivity becomes more reliable if the proper topology is chosen for the deployment [13]. The topology also affects the energy consumed by nodes in network. For example, if a network is designed in such a way that the wireless sensor nodes are distributed far from their neighbors and the sink, the nodes will require high energy budget to establish connections and communicate [13].

Wireless Sensor Networks employ mesh (also known as peer-to-peer), star, star-mesh, and tree topologies, as show in **Figure 3**. Static network topologies do not suffer from topological changes but they suffer from minimum battery power and MAC layer problems.

In a star topology (**Figure 3**), the nodes are one-hop away from the sink. The sink or base station is at the central point and all the nodes in the network broadcast data through the sink to other nodes in the network. The star topology is energy efficient when adopted in WSN projects. But in situations where the sensor nodes are far from the sink node, the sensor nodes in the star topology requires a ton of energy compared to multi-hop through mesh. The challenge with this topology is that it is susceptible to failures when the sink node fails [21].

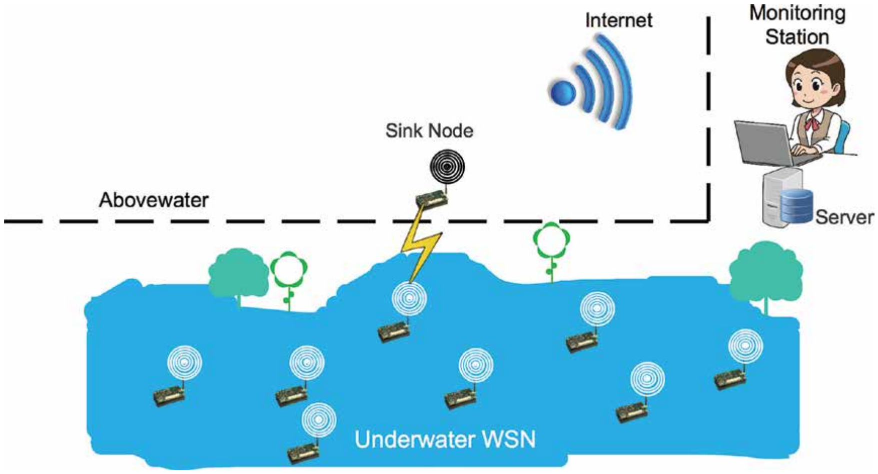

Figure 3.
Underwater deployment.

In **Figure 3**, the sink serves as the root of the tree and all other nodes are considered as child nodes. In **Figure 3**, the sink or base station is a hop away from some of the nodes, which are its nearest neighbors. The other nodes require multiple hops to reach the sink. In a full mesh, every sensor node is connected to every other sensor node in the network. Finally, in **Figure 3**, the sink node is at the central point. Some nodes broadcast to the sink directly whilst other nodes require a hop to reach the sink.

3. WSN deployment techniques

In WSNs, sensor node deployment is the process of setting up or positioning wireless sensor nodes to be fully functional and operational in either real-world using testbeds, laboratory or simulated environments [22, 23]. Deploying sensor nodes in the environment (i.e., land, air, water) may differ from one application domain to the other. In some cases, deploying the sensor nodes to communicate from one medium to the other (i.e., air/land to water, water to air/land, water to land and vice versa, and water to water) require the right selection of the deployment strategy [23].

The sensor nodes are deployed to collect data/information about their environment and transmit to a base station for onward processing. Nevertheless, the primary objective for node deployment consideration in WSN is to gain energy advantage since the sensor nodes are low powered devices. There are several deployment strategies for static and mobile sensor networks (**Figure 4**). Sensors in their physical environment play several roles in the network (i.e., act as a source node, relay node, cluster head, or sink/base station node) are deployed with any of the approaches or methodologies in **Figure 4**.

The objective function for selecting the desired methodology or approach should be based on the coverage area, network connectivity, network lifetime, and data fidelity (ensuring that the data gathered is credible) [24]. Unlike static environments, placing and controlling sensor nodes in mobile environments is challenging. Similarly, node replacement is also a difficult task. The best deployment strategy for any implementation must meet the following criteria: 1) have clear objectives to meet the application requirements; 2) improve system performance and maximization of network lifetime; 3) enable the detection of failures and errors in the network topology [13, 24]. Sensor node deployment techniques in WSNs may also be determined based on the algorithms used. Current algorithms that have gained proper consideration for sensor node deployment include greedy, adaptive, probabilistic, centralized, distributed, incremental, and genetic algorithms [25].

In [23], the authors classified four (4) possible WSN deployment problems that are likely to be encountered during the lifetime of the wireless sensor network (**Table 1**). The deployment problems were classified into: 1) node problems which general involve only one node; 2) link problems which occurs between two neighboring nodes; 3) path problems which typically occurs in a multi-hop environment (i.e., where paths are formed by more than three sensor nodes within the network); and 4) global problems affecting the entire sensor nodes in the network. Advances in algorithms for reduction in energy consumption, bandwidth utilization, routing and clustering, quality of service have seen the improvement of sensor node deployment issues related to coverage, network connectivity, energy efficiency, and data fidelity. A recent survey conducted by [26], has provided the state-of-the-art in four main wireless sensor node deployment strategies mentioned earlier in this dissertation and provides the approach, the load balance strategy, the lifetime, cost, redundant nodes, deployment space (i.e., 2D or 3D), the energy distribution, sensor range, and scalability of some of the work done so far in the area.

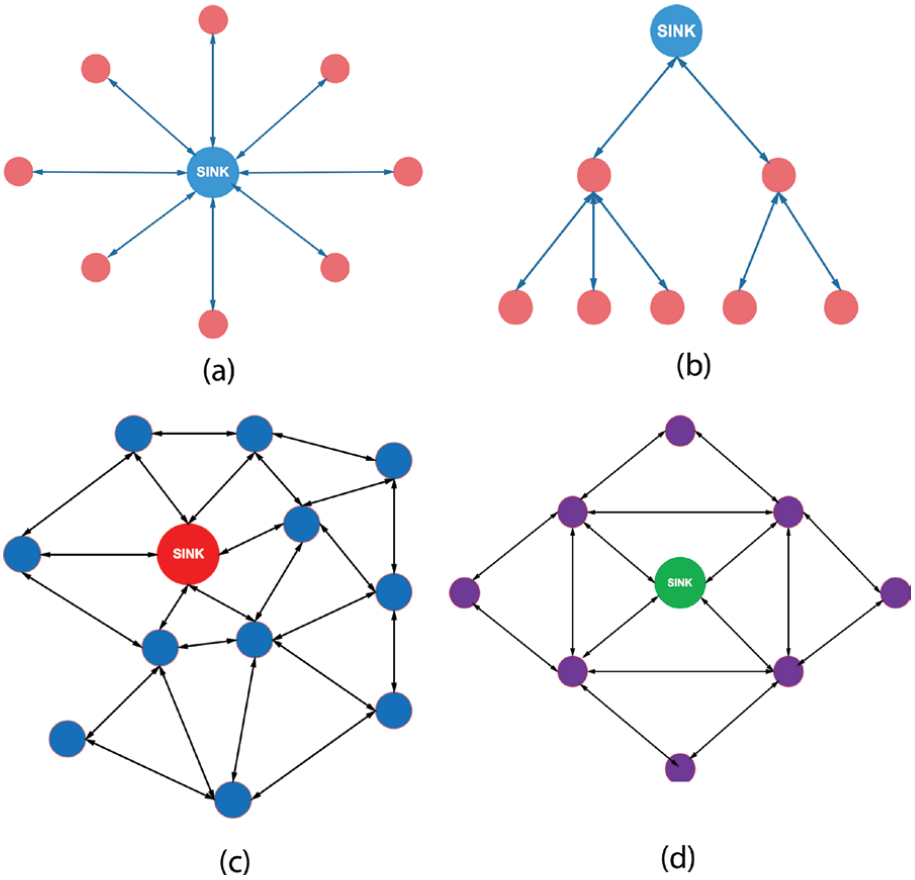

Figure 4.
WSN topologies. (a) Star topology, (b) Tree topology, (c) Mesh topology, and (d) Star mesh topology.

Sensor deployment problems	Causes	Effects	Possible solution
Node Problems	Low battery, increased network traffic, software bugs, and sinks acting as gateway between WSN and the Internet	Wrong sensor readings which affects the performance of the network; battery depletion due to overhearing, bugs results in hanging or kill threads, data loss	Node duty cycle Energy harvesting Power management schemes
Link problems	Network congestion due to traffic bursts, neighbor nodes frequently changing, asymmetric links	Message loss, broadcast to discover and maintain links	Efficient MAC protocol
Path problems	Bad path to sink bad path to node, routing loops, asymmetric paths	Greedy nodes not forwarding packets received message loss, inconsistent paths	Direct diffusion Rebooting nodes to clear cached data
Global problems	Low data yield High reporting latency Short network lifetime	Network delivering insufficient data Message loss Node dies	Energy efficiency schemes Energy harvesting

Table 1.
Sensor network deployment problems. Adapted from [3, 5].

4. Energy conservation

Energy conservation techniques or methods mitigate the consumption of energy from the sensor node through careful use of resources available to the individual components of the sensor node to reduce energy consumption. The different components that make up the subsystems of a sensor node are the sensing, computational and radio circuitry. The radio circuitry is responsible for operations such as transmission, reception, sleep and idle. The energy consumption of these afore mentioned components is presented in **Figure 5**.

The sensing component is made of sensor(s) for acquiring data from the environment that may include an analog-to-digital converter. The CPU with some memory is responsible for the processing of all computations and local memory allocations. Significant energy may be consumed by these components and subsystems, but the transmission and reception systems which are a function of the radio consumes the most energy.

4.1 Energy conservation schemes

Energy is a scarce resource in WSN applications and the judicious use of the energy available in a sensor node is important to ensure the continuous and prolonged use. Energy conservation schemes employ techniques to reduce the consumption of energy by the component. Classification of conservation schemes for energy in WSN mainly duty cycling, data-driven and mobility as shown in **Figure 6** [3, 27].

Duty Cycling approaches intuitively adapt the sleep/wake-up schedules of sensor nodes to mitigate the energy consumed through the distribution of overhead packets. This exchange of packets occurs during synchronization, frequent switching between sleep/wake-up schedules, overhearing and idle listening. Mobility schemes, however, consider the movement of the sink or relay nodes to positions closer to network nodes to reduce energy consumed. Mobility schemes are best discussed in mobility sensor networks in Section 5.

Figure 5.
WSN deployment techniques.

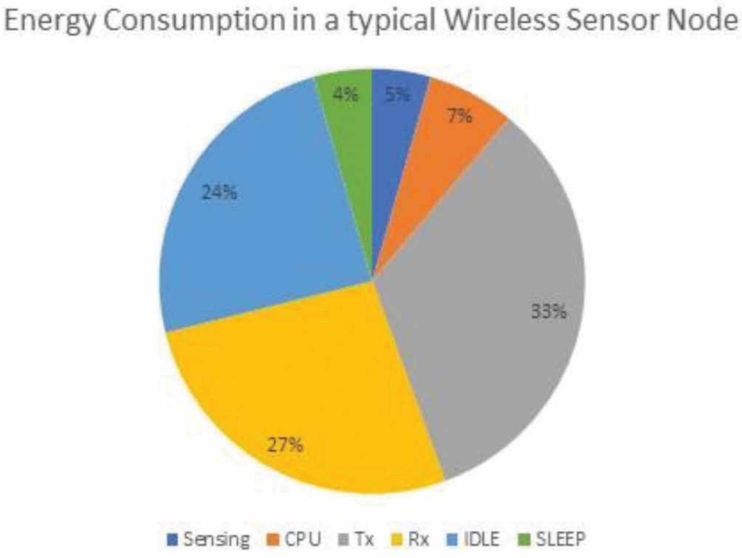

Figure 6.
Energy consumption by the components of a sensor node.

5. Mobility in wireless sensor networks

Mobility may be an important consideration in the energy conservation scheme of sensor networks. Mobility becomes necessary in energy conservation when the sink or nodes are mobile in the network [28, 29]. Static nodes with multi-hop communication usually have the energy hole problem where nodes closer to the sink are depleted of their energy [30]. The energy hole problem occurs when nodes further away from the sink use them as intermediate nodes to hop data to the sink. Mobile sinks, therefore, go round the network to collect data samples from the nodes to reduce the cost of communication and hence energy lost [31]. The challenge of implementing mobile sinks is to ensure optimum paths are maintained within the network [29].

5.1 Mobility models

The design, deployment and evaluation of sensor nodes in WSNs depend on the environment and the designed objectives for the intended application (e.g., water quality monitoring, fire detection applications, etc.). The sensor network in their deployable environments becomes successful when the stakeholders take into account the network size, the topology, and the communication models used for achieving the application goals. Mobile sensor nodes move to form mobile sensor networks and reposition/reorganize themselves in the sensor network. For example, nodes placed in the ocean are capable of measuring parameters such as ocean current speed, temperature, salinity, pressure, and other chemicals. These sensors move about collecting data in real-time and transmitting the data to a central repository for real-time data analysis [28].

Terrestrial WSNs mobility occurs differently from aquatic WSN mobility. For example, sensor nodes deployed in freshwater sources are affected by the water current. The node movement affects the sensor network design, the distance between the nodes (i.e., during route discovery), propagation, energy utilization among others. In an aquatic environment, electromagnetic wave propagation to sinks above water is challenging. Energy conservation and mobility in this type of network create challenges in the design of routing protocols. Routing protocols that are capable of minimizing the energy consumed by nodes, managing the random variation in the network topology and minimizing the delay in communication are therefore required in an aquatic environment.

In designing and evaluating mobility models for aquatic environments, our work took into consideration the conditions and characteristics of freshwater sources. Freshwater sources such as rivers are in constant motion. The velocity of the river depends on the slope of the land, the size and shape of the bed, and the quantity of water in the river [4, 32]. Sensor nodes may be deployed in one of the following environments; 1) slow but deep water bodies, 2) swift but deep water bodies, and 3) swift but shallow water bodies. Freshwater sources are characterized by three key factors: velocity, gradient, and discharge. Velocity is the distance that the water in a river travels in a given amount of time. The velocity relates to the energy levels of the water in the river. For example, objects (small or large) deposited in a swift or fast-moving river are carried downstream or along the river path quickly as compared to slow-moving rivers. The velocity of a river is affected by the gradient, discharge, and the shape of the river path that the water travels. The gradient is a measure of the steepness of a river, and a river's discharge is expressed as the quantity of water that moves through the different points along the river path at any given time. The discharge varies along the length of the river [32].

Mobile sensor nodes continue to move with water currents after the initial deployment. There are different mobility models used to simulate WSN projects. These include constant acceleration, constant position, constant velocity, Gauss Markov, hierarchical, random direction 2D, random waypoint, steady state random waypoint, random walk2D, and waypoint mobility models. Although these mobility

Terrestrial environment				**Aquatic Environment**
Parameters	**Random waypoint**	**Random walk**	**Random Direction**	**Modified random walk**
Selection of destination	Node selects destination (uniformly distributed)	Pre-defined destination (uniformly distributed)	MN travels to boundary of scenario (destination)	Region of interest
Selection of destination	To specified destination in environment	Selects a direction (uniformly distributed)	Selects uniform direction from boundary	Depends on water current (randomly chosen directions)
Selection of Speed	Selects speed (uniformly distributed)	Pre-defined speed (Uniformly distributed)	Selects uniform speed	Depends on river current/speed
Moving to destination	Moves until it reaches the destination	Node moves until reaching the boundary/a certain distance	Moves until it reaches the boundary	Nodes move to boundary and redirected by bouncing effects to change course (x, y)
Waiting time	Stays in a location for a period of time (Uniformly distributed)/Pause time	Wait a certain amount of time	Wait a certain amount of time	No waiting time since node movement is dependent on the flow motion
Next destination	Stays in a location for a period of time (Uniformly distributed)/Pause time	Node selects new direction after reaching boundary/ a certain distance	—	Node floating to the bank (Boundary) and bouncing effects determines (x, y) destination

Table 2.
Random mobility models compared.

models are designed for terrestrial WSN projects, they may be modified for use in aquatic WSN projects. In considering the random walk mobility model, the mobile sensor node after the initial travel time stays at a point for a given period known as the pause time. In other models, the mobile sensor node chooses a new direction and a new speed throughout the travel time and travels towards the destination with this new direction and speed. A comparison of some random mobility models and their characteristics are presented in **Table 2**.

Random walk mobility model is designed in a way that the mobile sensor nodes move freely and randomly in the defined simulation field. In our application domain (i.e., river network monitoring), the mobile sensor node's movement is affected by the characteristics of the water environment. Notably, the movement is affected by the velocity of the water. Therefore, the sensor nodes are not expected to move in a

- The time and distance that a mobile sensor node moves are short.
- The node's movement pattern is limited to an only small area in the simulation environment

- The node's directional movement is randomly generated
- The mobile sensor node moves independently of other nodes

Hence, there is a need to design models that have different mobility characteristics (i.e., such as destination, velocity, and direction). In an aquatic model defined in [33], the speed increases incrementally and the change in direction may not be smooth but fraught in some scenarios as shown in **Figure 7**. The Random Walk mobility model defined proposes node movements that depend on speed, discharge and gradient of the river. The speed and direction of the mobile sensor nodes are critical parameters that aids in the determination of a sensor nodes' mobility behavior.

Energy conservation schemes in WSN include approaches that depend on characteristics of the data values produced in the network to mitigate energy consumption. Data-Driven techniques, shown in **Figure 8**, involve the use of data characteristics of a sampled data stream to mitigate energy consumption [27]. They include data reduction and energy efficient data acquisition. While data reduction schemes save energy by taking out the redundant data, energy efficient data acquisition reduces the energy spent by the sensing subsystem or sometimes through communication.

Energy efficient data acquisition schemes work on the premise that the sensing subsystem, in some instances, consume significant amount of energy. These may include energy hungry transducers that require high power to sample data. Examples include multimedia sensors or biological sensor. Sensors that require active transducers like radar or laser rangers require active sensing and applications that require long acquisition time that may run into several hundred milliseconds or even seconds [33]. Reducing the energy consumption through frequent/continuous sensing translates into reducing the number of communication as well. The authors of [27, 34] argue that many energy efficient data acquisition schemes have been classified as methods to reduce the energy consumption of the radio. Therefore, WSNs assume the sensing subsystem has negligible energy consumption.

Data acquisition and reduction approaches have been used individually or simultaneously to mitigate energy consumption. The acquisition schemes measure data samples that are correlated spatially or temporally [35]. Temporally because subsequent data samples may not differ much from each other while data from neighboring sensor nodes may not differ much in spatial-correlation.

The inherent characteristics of the data that influence the data received at the sink may be classified as data reduction schemes. Data reduction approaches are generally categorized as In-networking processing, Data Compression and Data Prediction schemes. In-network processing applications are designed to be application specific. In-network data processing operations such as fusion and aggregation incorporate sensing and networking to reduce unnecessary data forwarding from

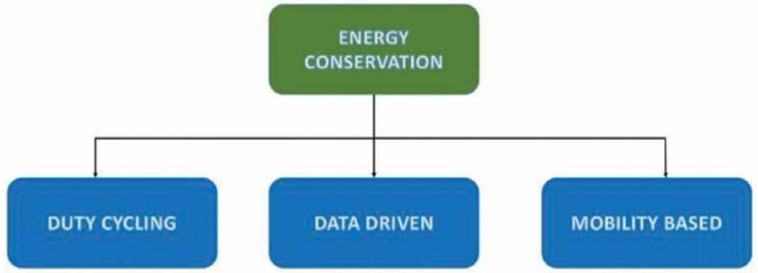

Figure 7.
Energy conservation in wireless sensor networks.

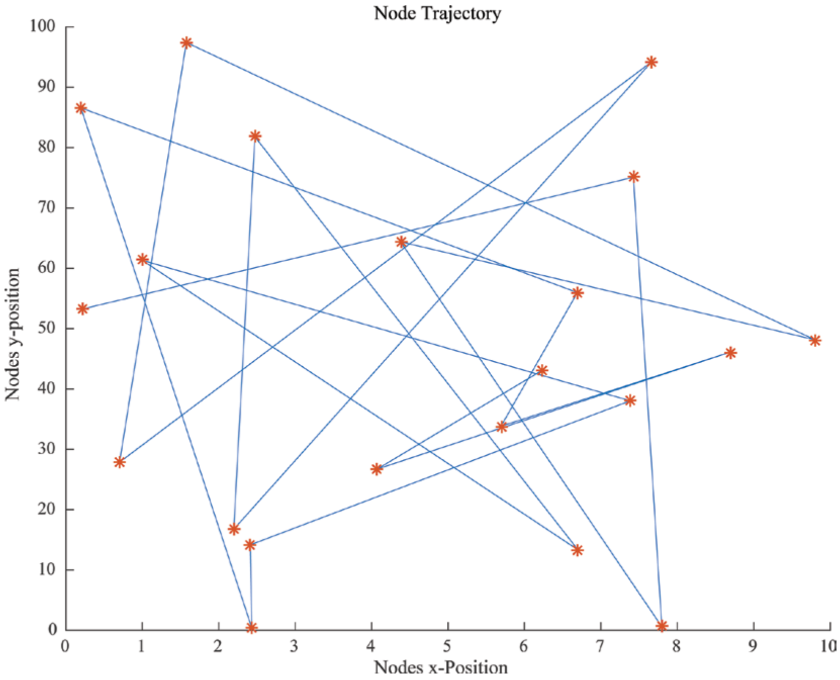

Figure 8.
Node mobility trajectory with random waypoint model.

source nodes to the sink as they traverse the network. A survey of data aggregation methods was presented in 36], and present clustering-based aggregation protocols in WSN. The clustering protocols were classified as homogeneous, heterogeneous, and single and multi-hop.

Data compression is the reduction of the amount of data that traverses a network. It may be classified into lossless, loss and unrecoverable compression. In lossless compression, the data obtained after decompression is the same as data after the compression operation [37]. An example of lossless compression is the Huffman coding. In loss compression [38, 39], some details of the data are changed as a result of compression. Unrecoverable compression occurs when no decompression operation is applied such final data cannot be derived from the initial data [40, 41].

6. Data prediction approaches

Data prediction is a data reduction method in WSNs that reduces the number of data that is sent from sources to the sink. They are concerned with the building of models for forecasting sensed parameters of sensor nodes using historical data. The main aim of predictive wireless sensor networks is to exploit the temporal and spatial correlation characteristics of the observed environment. Prediction also capitalizes on the redundancies of environmental parameters to compute future parameter readings thereby reducing the frequency of required readings.

The forecasted values are adopted when they fall within some acceptable thresholds. Some predictive models are based on the sink and on the nodes themselves. Prediction is therefore performed on the sink node and since the same model is kept on the nodes by synchronization, it is assumed the same predicted values are generated. In some instances, prediction is done by the nodes and model is sent to the sink; hence the sink also computes the same predicted readings. When nodes take readings beyond some threshold, it is sent to the sink otherwise the sink uses the predicted values. When the model deteriorates such that the model does not reflect the current readings, fresh data is read from the environment and the model is updated. This requires frequent update and re-synchronization of the sensor nodes and the sink which introduces energy consumption overheads in the network [2]. To overcome the energy lost by synchronization, some predictive models are only kept on the nodes, which determine when readings from the sensors are transmitted to the sink.

The prediction schemes surveyed in [22] on data reduction were not concerned with the medium access control challenges of radio energy consumption. In their classification, forecasting methods were not fully explored in WSN by the time of their publication as well as machine learning tools as argued in [42]. This is the basis for the new classification presented in **Figure 9**. Predictions studied in this chapter are limited to methods to predict data for the purposes for reducing data transmission (**Figure 10**).

6.1 Stochastic approaches

Stochastic approaches characterize the sensed data as a random process from which a probabilistic model is applied to predict the data values. An example of a stochastic approach is proposed in [43] where KEN (a range of perception, understanding and knowledge based model) a robust approximation technique minimizes

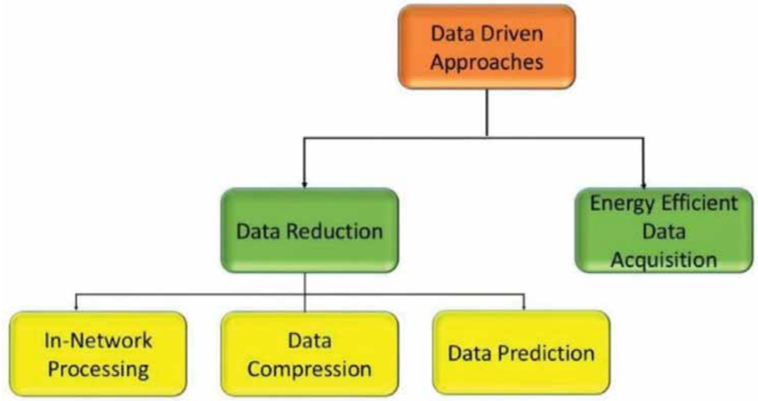

Figure 9.
Data-driven approaches in WSN.

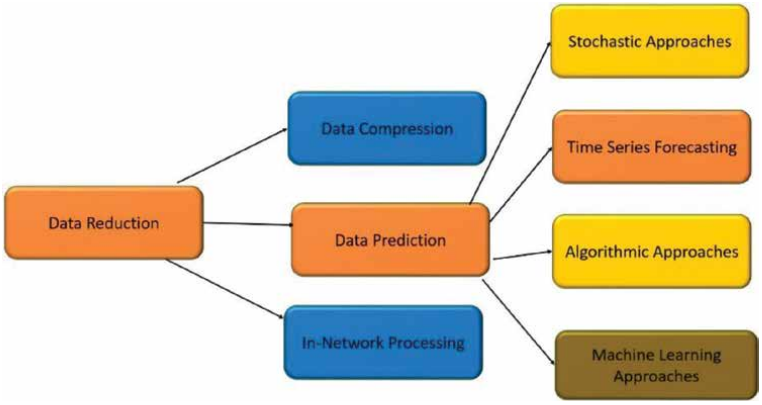

Figure 10.
Predictive approaches in wireless sensor networks.

the communication from sensors to sink using replicated dynamic probabilistic models KEN exploits the spatial correlations across sensor nodes to boost coordination that minimizes communication cost. The Kalman filter, Dynamic Probabilistic Models and Monte Carlo are some algorithms that have been used in some stochastic models [38, 39]. Due to randomness and probabilities of data used in stochastic applications, they are usually energy consuming and care must be taken in applying them to WSNs. They are mostly used in heterogeneous networks were specialized nodes that have high energy levels run these models.

6.2 Algorithmic approaches

Algorithmic approaches are predictive methods that depend on algorithms that consider the heuristic or behavioral characteristics of the data collected from the environment. One of the first works based on the algorithmic approach is Prediction-based Monitoring (PREMON) [44]. PREMON is a prediction-based monitoring algorithm which is inspired by concepts from MPEG (also known as the Moving Pictures Experts Group [MPEG]), a standard for video compression. Algorithmic approaches are usually application specific. A spatiotemporal data map of data stream from sensors at the sink node is obtained by generating periodic snapshots at a given time granularity [45]. An Energy efficient data collection framework (EEDC) is proposed in [46] that exploits the spatiotemporal correlation of data to form clusters and a randomized scheduling algorithm to conserve energy. A lightweight greedy algorithm that minimizes the energy consumed through data transmission is modeled as an optimization problem called Piecewise Linear Approximation with minimum number of Line Segments (PLAMLiS). The algorithm is integrated into EEDC framework to further save energy. In [47] a data collection method is proposed that exploits the trade-off between QoS of applications and energy consumption by progressively exposing power saving states in a network while minimizing the energy consumption. Since algorithms are application specific, more work may be done in the future in real applications to standardize the approaches. In [48], the challenge of selecting the efficient prediction model for a particular time series is addressed by an adaptive lightweight and online model selection algorithm. The algorithm statistically selects an optimal model among a list of candidates. The Dual Prediction Scheme (DPS) has been used severally in WSN applications and yield high communication and energy savings.

6.3 Machine learning approaches

Machine learning uses tools, techniques and algorithms with computational viability to improve on themselves by learning through their experience on data and is used for creating predictive models. They are able to carry out predictions while learning from streams of data patterns. Machine learning presents strategies for WSNs to better make informed decisions from the data in the network to improve network performance. These strategies learn the behavior of the networks and improve on its experiences of the environment without explicit programming. It is based on statistical models and probabilities to make predictions of future data occurrences.

In literature, machine learning approaches are categorized as supervised learning, unsupervised learning and reinforcement learning [Under supervised learning approaches such as K-nearest neighbor (k-NN), Decision Trees, Neural Networks, support vector machines and Bayesian statistics are the most commonly used Unsupervised learning techniques include K-Means clustering, and Principal Component Analysis (PCA). Reinforcement learning approaches have been used with the most common approach in WSN being Q-learning. Most of

Mechanisms	Classification	Machine leaning algorithms	Complexity	Balancing energy consumption	Delay	Overhead	Topology
Large scale network clustering	Supervised Learning	Bayesian Networks	Moderate	Yes	High	Low	Yes
Location-aware activity recognition			Moderate	Yes	High		Yes
Localization based on Neural Networks	Supervised Learning	Neural Networks	High				Yes
Soft Localization			Moderate				Yes
Cluster Head election	Supervised Learning	Decision Trees	Low	Yes	Low	Low	Yes
Underwater surveillance systems			Moderate				No
Clustering using SOM and sink distance	Unsupervised learning	SOM	Moderate	No	High	Moderate	Yes
Path Determination	Reinforcement Learning	Reinforcement Learning	Low				Yes
Role-free clustering	Reinforcement Learning	Q-learning	Low	No	Low	Low	No
Localization using SVM	Supervised learning	SVM	Moderate				Yes

Table 3.
Feasibility of machine learning approaches in wireless sensor networks.

these approaches have been applied in sensor node clustering and data aggregation mechanisms as presented in the **Table 3**.

In [46], the authors present surveys of machine learning approaches that have been applied to WSN to address known challenges such as outlier detection in data, computational efficiency, and errors in collected data. They are used in tasks including classification and regression and applied in bioinformatics, computer science, spam detection, anomaly detection, and fraud detection. Machine learning approaches have provided a means for wireless sensor networks to dynamically adapt its behavior to the environment. They are used to solve WSNs challenges such as limited resources and the diversity of the learning themes and patterns developed from the vast data collected. In [46], the authors identified challenges with machine learning approaches in wireless sensor networks which include developing lightweight and distributed message passing techniques, online learning algorithms, hierarchical clustering pattern and to develop solutions that take into consideration the resource limitation of WSN.

7. Sleep scheduling based on prediction

Sleep scheduling algorithms reduce the energy consumption in wireless sensor nodes due to idle listening and overhearing. Traditionally, sleep scheduling algorithms require frequent sleep/wake-up transitions; however, they consume extra energy due to the frequent state transitions. Sleep scheduling algorithms determine some nodes to be awake in a given epoch, while the remaining nodes maximize their sleep periods to reduce the energy consumed in the network.

Several sleep scheduling approaches have been proposed in literature since nodes in sleep (low power) modes consume significantly lower energy than active nodes. Some scheduling algorithmic approaches in literature propose means of turning off redundant nodes in the network, leaving some active nodes to continue network operations. Initial works include [49] where longer sleep cycles were proposed for a network with redundant nodes. The authors explored the relationship between the level of redundancy and the low duty cycles. The approach synchronizes nodes for a robust performance for large networks as opposed to a random scheduling approach. But the cost of synchronizing sensor nodes is high when the control overhead increases with increasing size of the network.

Idle listening, which occurs when nodes stay awake for longer periods waiting for packets, is a major source of energy waste in WSN. Authors in [49, 50] suggests idle listening consumes just as much energy required for receiving packets. Hence nodes are turned off when the radio module is not in use. Several approaches have been introduced by authors to mitigate idle listening.

One such approach is to put nodes in low-power listening (LPL) low duty cycle (LDC) mode (when nodes are made to sleep for longer periods when there is no activity in the network) that makes nodes wake up periodically to check the channel for activity. Characteristics of LDC include networks in periodic and relatively low frequency of network activity. One challenge of such networks is synchronization of receiver and sender nodes. Since sections of the network may be turned-off to conserve energy, remote communication may result in packets not reaching their destination, or have increased end-to-end delays. An example is Berkeley-MAC (B-MAC) makes nodes independently sample the channel for activity, by sending a preamble longer than the listening time of the duty cycle of the receiver node. This ensures the receiver is awake to receive its intended message. But this increases energy waste when the load in the network increases and collisions occur as a result of the increased preambles.

Low-power listening with Wake-Up After Transmission (LWT-MAC) was developed in [51] that alerts all nodes that overhead the last transmitted packets to wake-up to receive the new message. This approach does not depend on preambles but on the local synchronization of the nodes. This approach does not consider remote communication beyond the local nodes that overhear the latest transmission. Other protocols like X-MAC [52], S-MAC [42] and T-MAC [53] uses the Request-to-Send (RTS) and Clear-to-Send (CTS) to keep receiver nodes active when a message is intended for them. Other low-power listening protocols include Scheduled Channel Polling Mac (SCP-MAC) that increases the duty cycle after a successful message delivery to cut down on end-to-end delays.

TDMA protocols used in duty cycle algorithms reduce idle listening, over hearing and also avoid collisions. But they also increase the number of dropped packets in transmissions since nodes may only receive packets when they are active. Synchronization of receiver nodes and sender nodes ensures nodes are active to receive packets when transmitted from the sender nodes.

The medium access therefore is one key challenge in the era of Internet of Things (IoTs) due to the huge number of device connectivity with different traffic profiles. It is therefore, of necessity, an urgent requirement of these sensor nodes to reduce the number of transmissions from devices using data reduction approaches. However, prediction models, which forecast future data values may be a promising tool to reduce transmissions while maintaining optimum levels of trust and reliability of the data received [53].

In the past, researchers avoided the implementation of complex algorithms in WSN due to their limited computational capabilities. However, with recent advances in hardware, data mining techniques are increasing used in WSN to discover patterns in sensor data to improve on its successful delivery [54]. Even though not all data mining approaches include predictions, machine learning tools that implement prediction in WSN is currently an open research area. Authors in [54] discussed the implementation of machine learning in the routing and medium access layers.

In the implementation of prediction models, time series models have been used together with machine learning to forecast data values. This is because, machine learning-based approaches uncover and learn patterns in data to evolve their predictions in response to changes in the deployed environment. On the other hand, time series methods depend on the statistical and probabilistic tendencies of the data to make predictions. The survey by [55] introduced current prediction techniques for reducing data transmission in WSN.

Time series models sequentially model observed data over successive time. The successive data is analyzed to extract meaningful statistics and probabilities that may influence calculated forecasts. Time series data may be seasonal, trend, cyclical or irregular. Trend analysis tends to increase, decrease or remain stagnant over a long period. Seasonal analysis shows fluctuations that change during repeatable periods in the period under observation. Under cyclical, the patterns observed describe medium-term changes that may repeat in cycles, where cycles may extend over long periods. Irregular patterns fluctuate unpredictably and hence are difficult to be predicted using time series methods.

Examples of time series models implemented in WSN include the naive approaches, autoregressive and moving average approaches (AR and MA), Auto-Regressive Integrated Moving Average (ARIMA), Exponential Smoothing, Gray Series, and Least Mean Square (LMS). In time series analysis, Autoregressive Integrated Moving Average (ARIMA) generalizes the Autoregressive moving average (ARMA) with a differencing. However, ARMA is a combination of the Autoregressive (AR) and Moving Average (MA) models into a single equation.

Predictive Model	Examples	Classification of data	Characteristics	Advantages	Disadvantages	Applications in WSN
ARIMA models	AR, MA, ARMA, ARIMA	Seasonal, Trend	Univariate, linear and non-linear, discrete	Independence from external data. Does not require extended analysis	Assumes univariate data analysis	Data gathering applications Water Quality monitoring
Naïve algorithms	Naïve bayes	Trend	Distributed, partially independent	Independence of input data if trained. Useful in applications with frequent topology changes if model is well trained.	Assumes independent predictor features.	Medical data monitoring Agricultural monitoring
Exponential Smoothing	Single Exponential smoothing Double Exponential smoothing Triple exponential smoothing	Trends and seasonal data	Univariate	More significant to recent observations. Best for short-term forecasts	Ignores random variations of data. May not handle trends well	Environmental monitoring Multimedia VANETS
Gray Series	GM (1,1) Rolling GM (1,1) Adaptive Gray	Trend, seasonal,	Univariate and multivariate data.	Requires limited samples for short term prediction. Can make near accurate prediction with poor information of the data.	Homogenous exponent simulative deviation	Energy-map applications Water quality monitoring Environmental monitoring Internet of Things
Least Mean Square	LMS Hierarchical LMS	Trend	Univariate	Distributed algorithm Does not require a-priori knowledge of the environment	Not robust frequent change is trends	Target tracking Temperature measurements.

Table 4.
Time series classification.

These models are best for stochastic data sets that may be linear or non-linear. ARIMA models have several applications in WSN due to their simplicity of use, and near accurate prediction for linear data.

Exponential smoothing prediction is a time series forecasting method that can be used to forecast univariate data to support data with systemic or seasonal trends [56]. It is a model where predictions are weighted sums of past observations, such that weights exponentially decrease as they get older. Weights of predictions decrease at a geometric ratio. They may be considered peers or alternatives to other Box-Jenkins models. Three exponential smoothing models are generally used, that is the single, double and triple exponential smoothing models. The single exponential smoothing methods add no systemic structure to the univariate data without trend or seasonality. A smoothing factor, alpha is set to values between 0 and 1, with larger values indicating model is dependent more on recent observations and the vice versa. The single smoothing method is used when the observed data is either stationary or changes slowly with time.

The double smoothing method adds trends and seasonality to the univariate data. A beta value is added to the alpha value to control the decay of the influence of change in the trend of data. The change may be additive or multiplicative. When the change is additive, the Holt's linear trend model. In longer forecasts, the double smoothing method may reduce the size of the trend to straighten it, prevent unrealistic trends. In the triple smoothing, a gamma value is added to the alpha and beta to influence the seasonality of the observed data.

Gray series are time series prediction model with superiority to other statistical methods of prediction [57] due to its accuracy in predicting small data sets with lower errors. Gray models are preferable for data where statistical methods may not be appropriate or if the data does not satisfy conventional distributions [57]. In WSN, gray series are preferred due to their minimum complexity and low computational capacity. **Table 4** present some selected classification of time series models used in WSN based on their popularity and frequency of use.

8. Conclusion

The chapter focuses on the various deployment environments and the challenges that the implementation of WSNs brings about when adopted for use. The chapter also discussed WSN topologies and explored ways in which network topology impacts energy consumption and communication issues. The chapter highlights the different techniques mainly used when implementing WSNs to maximize lifetime, coverage, and connectivity while ensuring data fidelity. The chapter also describes the energy conservation techniques, data prediction approaches, and mobility models. Various data prediction models such as the time series models are discussed in detail. A classification of some time series models based on their popularity and recent use highlights their applications. Advantages and disadvantages of the selected time series models and reasons of their implementations are discussed.

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Section 3

Applications

Chapter 15

Innovative Wearable Sensors Based on Hybrid Materials for Real-Time Breath Monitoring

Mourad Roudjane and Younès Messaddeq

Abstract

This chapter will present the importance of innovative hybrid materials for the development of a new generation of wearable sensors and the high impact on improving patient's health care. Suitable conductive nanoparticles when embedded into a polymeric or glass host matrix enable the fabrication of flexible sensor capable to perform automatic monitoring of human vital signs. Breath is a key vital sign, and its continuous monitoring is very important including the detection of sleep apnea. Many research groups work to develop wearable devices capable to monitor continuously breathing activity in different conditions. The tendency of integrating wearable sensors into garment is becoming more popular. The main reason is because textile is surrounding us 7 days a week and 24 h a day, and it is easy to use by the wearer without interrupting their daily activities. Technologies based on contact/noncontact and textile sensors for breath detection are addressed in this chapter. New technology based on multi-material fiber antenna opens the door to future methods of noninvasive and flexible sensor network for real-time breath monitoring. This technology will be presented in all its aspects.

Keywords: wireless communication, wearable sensors, flexible antenna, innovative material, smart textile, breath monitoring

1. Introduction

Wearable sensors for vital signs monitoring are becoming key emerging technologies in different research fields such as medical science [1], sports and fitness [2], and military [3], to name a few. They present tremendous potential for providing a diagnosis of the subject's health status in their home, with the possibility to progress toward the concept of personalized medicine. The sensor is mostly made of conductive electrodes to detect the physiological signal, and it is an electronic device that seamlessly tracks and transfers all biometric data into an actionable base station with user interface for analysis and interpretation and data storage. Since two decades ago, tremendous efforts have been made in material sciences, radio frequency communications, and biomedical electronics research domains to transform these sensors as research and development laboratory tools to a commercial technology market. This transformation is driven by the urgent need to lower the high cost associated with health-care services in most countries, which continues to soar because of the increasing price of medical instruments and hospital care that would impose significant burdens on the socioeconomic structure of the countries [4]. Remote health-care noninvasive wearable sensors are ubiquitously alternative diagnostic tools for monitoring important physiological signs and activities of the patients in real time. New wearable devices with multi-functionalities are becoming more popular and are attracting more consumers. According to Idtechex's report on wearable sensors, the global wearable market is worth about 5 billion US dollars and is estimated to grow as much as 160 billions by 2028 [5]. Consequently, over the last few years, many companies developed and released to the market different wearable products in forms of smart watches, bracelets, skin patches, headbands, earphones, and fitness bands for unobtrusive, and when appropriate, continuous monitoring of some vital signs [6]. However, health data collected by these wearable devices suffer from inconsistencies and reliabilities that affect their usefulness and wellness for medical applications according to Erdmier, Hatcher, and Lee [7]. Wearable sensor for health monitoring systems can be integrated into textile fiber, clothes, and elastic bands or are directly attached to the human body [8]. The sensors are capable for measuring physiological parameters such as electrocardiogram (ECG), electromyogram (EMG), heart rate (HR), body temperature, electrodermal activity (EDA), blood pressure (BP), and breathing rate (BR) [9–11].

1.1 Remote health monitoring

The use of smartphones and tethered computers is now democratized worldwide and become a part of our daily life thanks to the recent advancement in mobile/computer technologies, which leads to a big change of every aspect of our lives starting from the way we work to social interactions. Remote health monitoring (or telemedicine) is no longer a science fiction as we used to see on our TV.

It starts to making initial inroads into health-care system. For example, a patient with chronic diseases, such as heart problems or diabetes, will continuously and simply monitor their health and send updates to their physician through the Internet. This can overcome the problem of infrequent clinical visits that can only provide a brief window into the physiological status of the patient. For a better acceptance of these technologies, wearable sensors' requirements must involve: comfort and ease to use, the ability to share the data with health-care professionals, very low energy consumption and long battery autonomy, and wireless communication with other devices [4, 12–17]. Remote health-care infrastructure is composed of wireless body area network, user interface smart digital assistant, and medical server for remote health-care monitoring system as illustrated in the general view architecture of **Figure 1**. In this architecture, a two-stage communication is used to transmit the health metrics recorded by the sensors to the remote health-care server. In the first stage, a short-range communication protocol is employed to transmit the measured data to a nearest gateway, such as smartphone, computer for advanced data processing, and display. The second stage consists of long range communication where the processed signal is transmitted to a server located in a health-care facility. The data can be transmitted over the Internet or cellular communication network such as general packet radio service (GPRS), 3G/4G, or Long-Term Evolution (LTE) services [18–20]. With the miniaturization of the electronic devices and powerful mobile computing capabilities, individuals are becoming capable of monitoring, tracking, and transmitting health biosignals continuously and in real time. These technologies will open a new era for humanity in particular when the access to medical centers and hospitals is more restricted such as in the case of a viral infection becoming a global pandemic.

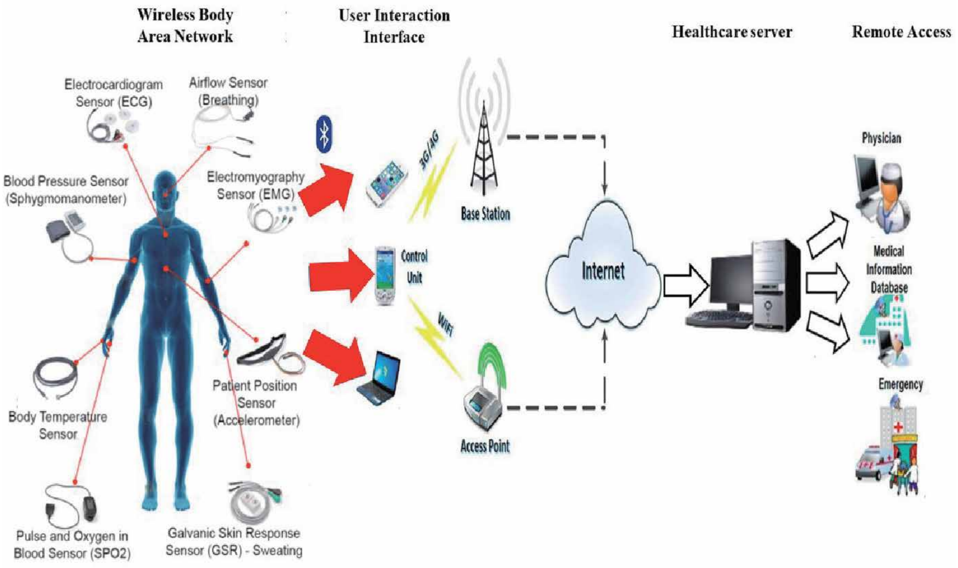

Figure 1.
General overview of the remote health monitoring system from. It is based on a wireless body area network, a user interaction interface, a healthcare server, and a remote access for medical professionals.

1.2 Human breathing mechanism

In general, breathing (or respiration) is an important physiological process of living organisms. It is defined by four parameters: inhalation time, exhalation time, breathing period, and breathing rate. For humans, this process results in air exchange between the lungs and external environment. It consists mostly of inhalation of oxygen through the nose or mouth into the lungs and flushing out carbon dioxide during exhalation. The entire process from the inhalation to exhalation is known as a breathing cycle. During breathing, inhalation is caused by the contraction of the human diaphragm which causes the intra-thoracic pressure to fall due to the enlargement of the thoracic cavity. The latter induces lung expansion due to inhalation. Once the gas exchange occur across the alveolar-capillary membrane [21], the exhalation of carbon dioxide allow the diaphragm and inter-costal muscles to relax. Consequently, the chest and abdomen return to the rest position.

1.3 Importance of breath monitoring with wearable sensors

Many evidences demonstrate the importance of breathing rate as a key parameter. It is an important indicator used to monitor the progression of illness. An abnormal BR has been shown to be an important predictor of serious events such as cardiac arrest and admission to an intensive care unit [22]. Besides, it is fundamental in the early detection of the risk of the occurrence of dangerous conditions such as sleep apnea [23], respiratory depression in post-surgical patients [24] and sudden infant death syndrome [25]. It was reported by Fieselmann et al. that a BR higher than 27 breaths/minute was the most important predictor of cardiac arrest in hospital wards [26]. Monitoring of breathing signal is also very important during anesthesia for evaluating sleep apnea disorders [27]. In addition, Tas et al have pointed out the importance of continuous monitoring of BR to study the effects of heroin administration with addicted person in order to avoid any heroin-induced respiratory depression during the treatment [28]. Although, BR is of paramount importance when assessing the health of a patient, it is still often measured clinically using a flow-meter embedded in a mouthpiece, or a mask rather than wearable and noninvasive devices with a continuous monitoring capability [29]. Therefore, technological development and clinical validation of new wearable sensors is more than urgent to feel the gap between the need of accurate and continuous measurement of breathing patterns and rate and the clinical practices [30]. This chapter covers the description of different classical techniques used for continuous monitoring of breath, and the new generation wearable sensor counterpart developed using different hybrid materials. The goal of this chapter is to make a clear and comprehensive review on the new generation of wearable sensors made of new flexible and biocompatible materials.

2. Wearable sensor classification

Wearable sensors can be classified into two categories: invasive and noninvasive. Invasive wearable sensors can be further classified as minimally invasive, such as subcutaneous electrodes to obtain the electromyography (EMG) signal, or as an implantable, such as a pacemaker. These kinds of sensors require a clinical intervention to place them inside the body. Noninvasive wearables may or may not be in physical contact with the body. These sensors are typically used in systems for continuous monitoring because they are ease to use and often do not require lots of assistance from a health-care professional. They could be in form of watches, bands or integrated into textile. Noncontact breath monitoring methods are becoming more popular since they have clear advantages over the contact methods. In the former, the patient comfort is taken into account, especially for long-term monitoring and improved accuracy as distress caused by a contact device may affect the breathing rate measurements.

3. Classic sensors: from bulk to flexible form

Classic sensor refers to the sensors often used by clinicians and health professionals to estimate the breathing frequency and pattern in the clinics or hospitals. In this section we will present these sensors in their original bulky and rigid form, and their innovative version based on plastic electronic technology. The latter are more soft, lightweight, and stretchable enabling applications that would be impossible to achieve using the bulky forms.

3.1 Respiratory airflow sensors

Airflow sensors are largely used in clinics and hospital for collecting the pattern trend of inhaled and exhaled air during breathing. The technology is based on measuring the amount of air inhaled and exalted using different mechanisms such as differential flowmeters for monitoring gases delivered by mechanical ventilators and recorded by commercial spirometers [31, 32], turbine flowmeters [33], and hot wire anemometers [31], similar to the differential flowmeters, and it consists of heated wires exchanging heat with the fluid flow. These sensors require often the use of mouthpiece which is uncomfortable for long-term use. In addition, they cannot be used for continuous monitoring of breath.

The exhaled breath composition is complex, and it includes mainly a mixture of nitrogen, oxygen, CO_2, water vapor, and other components' traces such as volatile organic compounds (VOCs), acetone, carbon monoxide, ammonia, and nitric oxide

[34]. For instance, breath carbon monoxide test was used for neonatal jaundice diagnosis [35], breath ammonia was proposed for assessment of asthma and hemodialysis [36], and breath VOCs were used for the diagnosis of ovarian cancer [37]. A portable device for measuring human breath ammonia was developed based on a single use, disposable, inkjet printed ammonia sensor fabricated using polyaniline nanoparticles [38]. More recently, a novel miniaturized sensor based on organic semiconductor material was developed and successfully tested to monitor ammonia breath [39]. Flexible sensing platform based on the integration a self-healable polymer substrate with five kinds of functionalized gold nanoparticle films was used for sensing pressure variation as well as 11 kinds of VOCs [40]. A novel wearable electronic based on flexible printed multiwalled carbon nanotubes (MWCNTs)/ polymer sensor array was designed as a compact armband to detect VOCs as well [41]. Despite the development of flexible electronics for breath sensing, many challenges need to be addressed for technology acceptance. For example, the biomarkers exhaled from breath may suffer from the interference from humidity or contamination from ambient air. In addition, most of the proposed sensors were tested in a controlled work place which is not the case in real-life conditions. Lastly, the proposed technologies was not tested for real-time breath monitoring. As consequence, the future wearable sensors shall address all these issues.

3.2 Respiratory inductance plethysmography sensors

This noninvasive method is based on tracking the chest and abdominal wall movements during breath to measure the changes in circumference during respiration which is directly related to the tidal volume [42]. The sensor consists of two bands placed around the abdomen at the level of the umbilicus and over the rib cage. The bands are made from a flexible conducting material used as strain gage, and the concept was first developed in 1967 and has since been established for monitoring patients in a clinics and hospitals [43]. The principle of the strain gage sensor is based on the change of the conductor resistance when it is subject to external force such as the case during the breathing process. Stretchable strain gage sensors have been developed based on various transduction mechanisms [44], such as capacitive [45] piezoelectric [46], and piezoresistive sensing [47]. A miniaturized strain sensor composed of a piezoresistive metal thin film set in a silicone elastomer substrate with a footprint smaller than that of a typical Band-Aid was developed [48]. Breathing rate and volume were measured by sticking one sensor on the rib cage and the other sensor on the abdomen.

More recently, nanomaterials have been shown to be promising as innovative strain sensors, and are based on nanoparticles building block based on CNT [49], graphene [50], and silver nanowires [51]. However, this technology has its limitation in monitoring patients throughout the day because the bands prone to slippage, which alter the breathing measurements.

3.3 SpO2 oximeter

SpO2 oximeter is another noninvasive method used to measure accurately both oxygen saturation in the blood and heart rate, and is widely used in hospitals and clinics to monitor patient at risk of hypoxia [52]. During breathing process, the inhaled oxygen binds to the hemoglobin in red blood cells, then it is transported throughout the body in arterial blood. The SpO2 pulsed sensor uses two light sources emitting typically at 660 (red) and 940 nm (infrared) to measure the percentage of hemoglobin in the blood that is saturated with oxygen using internal detector. This percentage is called blood saturation, or SpO2 [53]. The breathing rate is determined accurately using wavelet analysis technique of the plethysmogram as demonstrated by Leonard et al. [54]. The bulky wearable oximetry sensors used actually in clinics and hospitals are often placed on the finger, or wrist, but could be also on head, earphones, thigh, and ankle, and they have been widely commercialized [55].

The clinical oximeter versions are of portable size. However, a lot of efforts in material science and electronics were made to develop new versions at a wearable size able to monitor accurately the oxygenation. Recently, an electronic patch oximeter capable to perform the oxygenation sensing and communicate the data via wireless protocol was developed and successfully tested [56]. The electronic patch could be attached on different parts of the skin surface. Furthermore, an all organic optoelectronic oximeter sensor was designed with organic materials on flexible substrates to measure accurately the pulse oxygenation [57]. Ultraflexible organic photonic skin oximeter, and a miniaturized battery free flexible and wearable pulse oximeter were also reported recentely [58, 59]. The optoelectronic skins are extremely thin, lightweight and stretchable. Nevertheless, the patch-based technology is still at the research and development level and requires more improvement for long-term monitoring since patches may cause irritation for some people.

3.4 Electrocardiogram sensors

Breathing can be derived from an electrocardiogram (ECG) signal by measuring the electrical activity generated by the action potentials in heart muscle at each heartbeat [30]. The body-surface ECG is influenced by electrode motion with respect to the heart and by changes in thoracic electrical impedance of the lungs (air in and out), which is well-correlated with breath [60]. The breath is derived from the ECG fluctuations and this technique is called ECG-Derived Respiration (EDR) [61]. The ECG signals has for many years acquired using conventional wet silver-silver chloride (Ag/AgCl) electrodes which convert ionic current on the skin surface to electronic currents for amplification and signal processing [62]. The signal is recorded by measuring the voltage difference between two or more electrodes on the body surface over time [63, 64]. Although Ag/AgCl electrodes are cheap and disposable, they require the use of a conducting gel between the electrode and the skin. This may cause several problems related to the comfort of the users when used form long time, and signal corruption and base line drift caused by the change of the chemical properties of skin-electrode contact surface [64, 65].

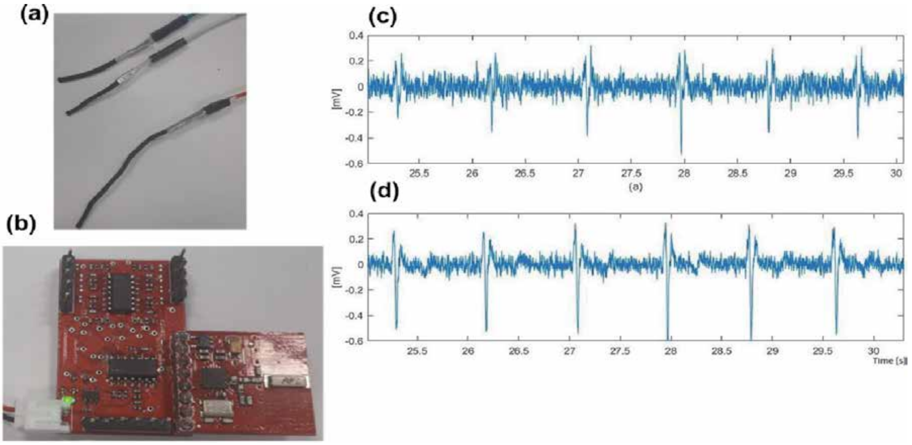

Figure 2.
Noninvasive ECG sensor made of flexible conductive fiber electrodes (a) connected to a wireless electronic system (b). ECG signals acquired with the conductive fiber (c) and with the Ag/AgCl electrodes (d) [68].

Flexibility of the electrodes is an important characteristic to achieve a better skin-electrode interface and to provide comfort to the users. Polymer dry electrode based on polydimethylsiloxane (PDMS) coated with metals such as Ti:Au [65], copper [66], and CNT [67] were previously developed. More recently, a biocompatible conductive polymer fiber doped with CNT was used to fabricate flexible and dry fiber electrodes for biopotential signals detection [68]. The ECG signal detection with these fiber electrodes was reported for the first time as shown in **Figure 2**, and their performance against moisture revealed no change in the quality of the detected signal in terms of signal-to-noise ratio. Nevertheless, the proposed system needs further development for medical application in particular the electrical sensing board.

Other contact-based methods were proposed such as humidity sensors, acoustic sensors, and air temperature sensors which are all reviewed in [30].

4. Imaging and microwave-based sensors

Beside the classical sensors, significant efforts were made by scientists to develop new noninvasive and contactless sensors capable to monitor breathing parameters. New approaches based on recording the chest and abdomen movements during breath using either camera imaging or microwave-based Doppler radar were proposed. For camera imaging, the working principal is based on evaluating posture changes and breathing rate of a subject often laying on a bed. For instance, infrared thermography based on wavelet decomposition [69], thermal imaging [70], camera-based systems [71], real-time vision-based methods [72], and a 3D vision tracking algorithm [73] were developed to measure the breathing rate in real time. For the microwave-based Doppler system, a radar source emitting pulsed or continuous microwave signal toward a subject, and the basic principle is that the Doppler radar signal reflected from the monitored subject is phase modulated by the subject's respiration and heartbeat. Continuous wave narrow-band radars [74], ultra-wide band (UWB) radars [75], and passive radar techniques [76] were proposed.

5. Textile as innovative sensors platform

Human-worn cloths since his birth, and they are considered as the first skin protection interface from the external environment. Clothing usually covers large parts of our body, and it was proposed for the first time in 1996 as the most appropriate platform to implement wearable systems for the unobtrusive monitoring of vital and bio-physiological signals [77]. Using conventional fabric manufacturing techniques (weaving, knitting, embroidery, and stitching), the combination of wireless communication sensing devices with functional yarn and fibers into a garment gives rise to the so-called smart textile (or electronic textile). A good smart textile is the one that has the capability of sensing accurately the external surrounding environment, while maintaining the same mechanical properties of a traditional garment. Based on the desired functionality, smart textile are divided into three categories: passive smart textile, which is considered as first generation model, has the minimum requirement for sensing an external stimulus, such as detecting the change of the external temperature; active smart textile is the second generation model with the capability to sens the surrounding environment such as temperature, light, odor, and reacts using various textile-based flexible and miniaturized actuators; finally, ultra (or very) smart textile is the third generation

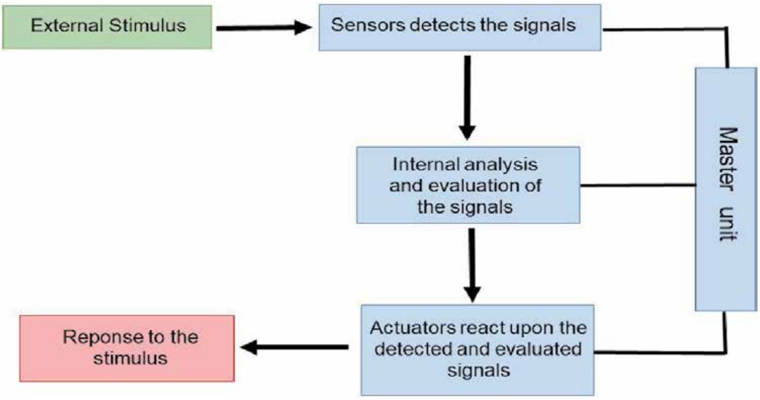

Figure 3.
Working principle of an active smart textile.

textile capable to sens, react, and adapt to the situation based on the learned experience from what it sensed and reacted to previously. Smart textile working principle is described in **Figure 3**.

5.1 Functionalized textile as electrodes

Smart textile is an important alternative which provides a more conformable and user friendly approach for breath monitoring. Textile-based dry electrode were reported to be as efficient and reliable as Ag/AgCl wet electrode [78]. They are made of conductive yarn that can be knitted in plain [79], honeycomb weave patterns [80], embroidered [81], or screen-printed directly onto fabric [82]. Conductive thread electrodes are often integrated into garment and connect to wireless electronic systems for data acquisition and transfer, which make their usage more easy and comfortable. The first smart textile platform based on knitted integrated sensors was proposed in 2005 [83]. The platform was able to acquire simultaneously, and in a natural environment, ECG, breathing activity, posture, temperature, and movement index signals. Later on, many researcher groups proposed smart shirt based on different type of conductive electrodes to measures ECG signal [80, 84], or textile piezoresistive sensor for detection of respiratory activity [85], such as the case for the European project Psyche a personal, cost-effective, multi-parametric monitoring system based on textile platforms and portable sensing devices [86]. However, these type of electrodes exhibit permanent performance degradation and significant reliability issues after repeated washing cycles, poor resistance to strain, and sweat oxidization problems in particular for silver-plated fibers [64, 65]. As a consequence, functionalized polymer-based sensors integrated into textile were proposed as an alternative solution. Weft-knitted strain sensor made from silver coated nylon was used to fabricate a belt, which can be worn around the chest or abdomen to monitor breathing rate [87]. Triboelectric nanogenerators (t-TENGs) was integrated into T-shirt garment by direct weaving of Cu-coated polyethylene terephthalate (Cu-PET) warp yarns and polyimide (PI)-coated Cu-PET (PI-Cu-PET) weft, to fabricate a chest strap for real-time breath monitoring [88]. Conductive silicone strap integrated into garment was also for breath monitoring [89].

5.2 Optical fibers for sensing

The development of smart textile requires further improvement of the functionalities of its fiber component. Recent advances in optical fiber technology did not only revolutionize the worlds of lasers and communications, but also the world of fashion and smart textile. In fact, when optical fibers were embedded into textile composites using either weaving or knitting manufacturing techniques [90], they give more functionalities to the garment such as light emitting for wearable luminous clothing [91], environmental conditions [92, 93], and health-care [94] monitoring. Using optical fiber, the breath monitoring principal is based on the changes of the optical properties of the light passing through the fiber during the expansion and contraction of the thorax and abdomen. These changes are caused by the increases of the fiber losses due to microbending [95], which enable the fiber to be used as a sensor. Flexible polymer optical fibers (POFs)-based sensor have been used previously for breath monitoring [96–98]. The POF-based sensors present some advantages such as the absence of electrical interference, in particular when used during magnetic resonance imaging [95], and good flexibility [99]. Moreover, highly flexible POFs was integrated into a carrier fabric that react to applied pressure to form a wearable sensing system [100]. Other types of optical fibers which have been implemented in the wearable sensor include: fiber Bragg grating (FBG) [101], macro-bending of single-mode fiber [102], and notched side-ablated POF on a fabric substrate [103]. With the FBG, a smart garment featuring 12 FBG sensors to monitor breath and heart rates was proposed and validated with gold standard instrument with both gender [101, 104]. However, this wavelength detection-based technology is very complex, and the fabrication technology of the sensors is very expansive, which jeopardizes the large scale manufacturing. Furthermore, the cable connection between the smart T-shirt and the optical spectrum interrogator reduces the mobility of the user and could create a discomfort when used for a long time.

6. New generation of intelligent textile

Wireless communication is one of the most critical requirement in the development of smart textiles as it eliminates all the mobility restrictions [105]. This communication is assured by an antenna, a key component for any wearable system. Embedding antennas into textile transform the garment into a user-network interface [106]. Several textile antenna designs were proposed for medical applications in the industrial, scientific and medical (ISM) and ultrahigh band, such as inverted-F antenna inkjet printed on fabric [107], flexible and stretchable patch square shape antenna on a 3-D printed substrate [108], and epidermal patch antenna [109]. With the rapid progress on the fabrication of conductive textile, silver yarn was used to create a 2.45 GHz spiral shape antenna integrated into textile and connected to an electronic system for heart rate monitoring, fall detection, and ambient temperature measurement [110]. Although the proposed wearable antennas were enabling radio frequency communication when connected to an electronic board, their weak performances and poor endurance to environmental conditions, such as moisture [111], require further improvements for future applications.

6.1 Development of new antenna

An efficient wearable antenna should fulfill important requirements such as thin thickness, robust, lightweight, and resistant to washing cycles. Moreover, it must be low cost for manufacturing [106]. Following these criteria, a next-generation fiber antennas that lend themselves to RF emission [112, 113] adaptable to existing civilian broadband mobile infrastructures was developed exclusively for real-time breath monitoring when integrated into textile. Four different antenna shapes were designed for a 2.45 GHz emission frequency: a leaky coaxial cable (LCX), a central fed-dipole, a loop, and a half-turn Archimedean spiral fiber. These antennas were fabricated using an inert hollow-core Polyimide-glass fiber of 362 μm diameter functionlized by plating the external and internal surfaces with thin films of conductive nanoparticles. For the LCX antenna, shown in **Figure 4(a)**, the external surface of the capillary was plated with 20 μm copper thin film using electrochemical deposition, and the internal surface was coated with 150 nm of silver layer using a redox chemical reaction [112]. Dipole, loop, and spiral fiber antennas were fabricated using the same hollow-core Polyimide-glass fiber and using the same silver deposition technique of the inner capillary as presented in **Figure 4(b)**. The schematic representations of these antennas are shown in **Figure 4(c)–(e)**.

The designed antennas were integrated into textile as shown in **Figure 4(f)** using different techniques. The LCX, dipole, and loop antennas were weaved using a computerized loom, while the spiral fiber antenna was sewed into a textile. The metal-glass-polymer fiber permits the antenna integration into a textile without compromising comfort or restricting movement of the user due to its flexibility.

The emissive properties in free space, and the gain of the designed antennas were investigated both experimentally and numerically, and it was found that the central frequencies of these antennas were around 2.45 GHz, with a gain of 1.76 dBi for LCX, 1.76 dBi for loop, 3.41 dBi for dipole, and 2.37 dBi for spiral fiber antenna [112–114]. For environmental endurance, the used composite metal-glass-polymer fiber shields efficiently the antenna from the external perturbation, and it becomes more sustainable to moisture effects when additional superhydrophobic coating was added to the antenna external surface and to the surrounding textile [115]. Further studies on the resistance of the antennas against external deformations have shown that the spiral fiber was more sensitive in comparison to the rest of the antennas, with a central frequency shifts of about 360 MHz [113, 114].

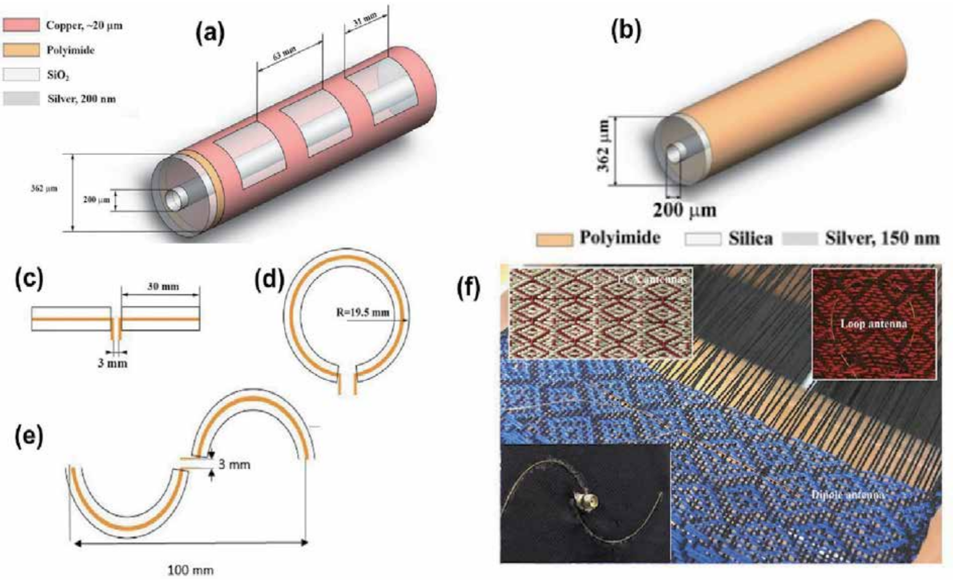

Figure 4.
(a) Structure of the LCX fiber antenna; (b) structure of the polyimide-coated hollow-core silica fiber. Geometry of (c) linear dipole, (d) loop, and (e) spiral fiber antenna fabricated from the conductive multi-material polyimide hollow-core silica fiber and designed for the 2.4 GHz communication network. (f) LCX, loop, and dipole antennas weaved into a cotton fabric (top).

6.2 Wireless communicating textile

The high sensitivity of the spiral shape antenna enables it to perform extra duty in addition to its classical role. Indeed, it has been demonstrated for the first time that when this antenna is integrated into a T-shirt on the chest position (see **Figure 5(a)**), access to breath monitoring was possible through the continuous measurements of its central frequency shift, which is induced by the movement of the chest during breath [114, 116]. As shown in **Figure 5(b)**, the movement of the chest causes deformation to the antenna shape, and the central frequency shift is continuously measured with a vector network analyzer (VNA) and plotted against time as presented in **Figure 5(d)**. A strong correlation between the frequency shifting and the breathing periods were observed [116].

Improvement were introduced to the T-shirt to make it more comfortable for daily use by developing a new smart textile featuring a breath sensor based on Bluetooth communication protocol as shown in **Figure 5(c)**. Breath monitoring was measured from the received signal strength indicator (RSSI) (see **Figure 5(e)**) emitted by the sensor, made of spiral antenna and a Bluetooth transmitter, and detected by a base station. The breathing patterns and rates were estimated after data processing of the RSSI signal using Fast Fourier Transformation (FFT) method [114].

Although the new wireless communication smart textile meets most of the requirements for a reliable and efficient portable system, its capabilities for an accurate monitoring of breath required further development. In fact, detecting breath using only one sensor placed on the middle of the chest is not enough because the breathing mechanism induces the displacement the chest and the abdomen, and the latter was not detected by the smart textile.

To enhance the performances of the smart textile, a new design featuring an array of six sensors was proposed [117] as shown in **Figure 6(a)**. The sensors were

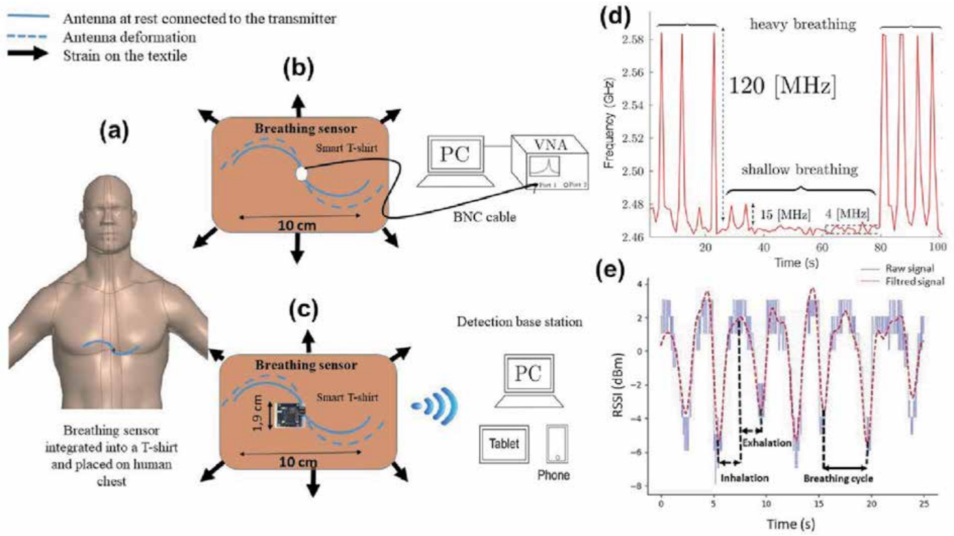

Figure 5.
Schematic representation of the working principle for breath detection: (a) breathing sensor is placed on the chest of human body; spiral antenna configuration change under the stretching load caused by the chest expansion during the breathing; (b) and the induced central frequency shift is measured using a VNA, (c) or through the RSSI signal detected wirelessly a base station. (d) Resonant frequency shift of the multi-material fiber spiral fiber antenna integrated into textile as a function of time during breathing pattern measurements. (e) Breathing signal from received signal strength indicator (RSSI) measurements (blue) and the processed signal (red).

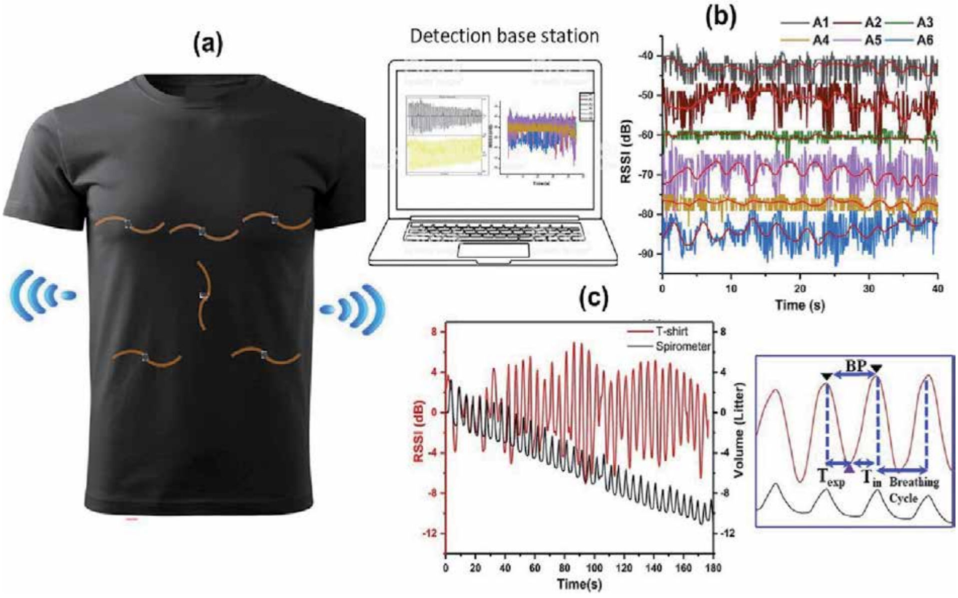

Figure 6.
(a) Breathing sensor array integrated into a stretchable T-shirt together with the portable base station for signal detection; (b) raw and smooth RSSI signals recorded with the smart T-shirt based on the sensor array Ai (i = 1–6); and (c) breathing pattern obtained from the received and filtered RSSI signal recorded using the wireless communication smart T-shirt (red), and the standard reference (black). The inset, the experimental measurements of the breathing parameters.

installed strategically on both left and right sides of the thorax and the abdomen to monitor breathing from both compartments (see **Figure 6(b)**). The emitted six RSSI signals are displayed and plotted in real-time on the detection base station. The breathing pattern were then extracted from the analysis of an RSSI trace based on two criteria: a large variation of the RSSI amplitude, and a clear RSSI signal oscillation. The validation of the new textile was performed by direct comparison with a flow meter used as a medical gold standard reference. A statistical analysis based on Bland-Altman analysis [118, 119] showed a good agreement between the breathing parameters measured with the smart T-shirt and those with a standard reference system. An example of breath-to-breath comparison is displayed in **Figure 6(c)**. These two synchronized signals present similar oscillation of the corresponding signals during the breathing process, and both systems record accurately 37 breathing cycles during the test. These experiments were performed with seven volunteers of different in both standing and seating postures. In addition to breath monitoring, the new textile was also capable to monitor successfully stimulated apnea by stopping breathing for a short period of time during breath detection [117].

7. Data processing and machine learning

Signal processing is a very crucial step to extract breathing patterns and parameters. This step is as important as the development of the wearable acquisition system, and the choice of the processing method can define the quality and accuracy of the output results. Signal processing could be performed either in real time using algorithms integrated into the processing unit of the wearable sensor, or performed off line by applying different transformations on the stored data. Data processing will depends on the sensing technology. For example, in the case of facial tracking sensor [73], image processing techniques were used to enhance the recorded thermal images and to remove unwanted noise, while for the wearable patch sensor network [120], real-time data processing and fusion algorithms integrated into the processing units were used. Most, if not all, processing methods are based on filters. Filters are often used in bio-physiological applications such as for the spectral contents of ECG signals [64], or for vital sign detection such as RSSI signals [114]. For breath signal, the spectral frequency range is well known, and signal filters can be applied to the raw data to minimize high-frequency noise while preserving the breathing envelope signal. A band-pass filter with cutoff frequencies of 0.05 and 1.9 Hz is applied to compensate for possible drifts and to reduce the noise level in the signals [64]. FFT algorithms, that converts the signal from the time domain to the frequency domain and vice versa, are then applied to extract the spectral features such as breathing rate.

Machine learning was proposed as another alternative method for breath monitoring. This method is based on pattern recognition and capabilities of computer machines to learn and execute a task. For instance, Convolutional Neural Network (CNN) method was used in identifying asynchronous breathing [121]. The results were very satisfactory (sensitivity of 98.5% and specificity of 89.4%) when trained with different amount of training data sets and different types of training data sets. Deep neural network (DNN) is another methods used for the firs time to improve phone recognition [122]. It has been demonstrated that when the DNN-based fine-grained algorithm is integrated into smartphone for acoustic recognition, and the breathing rate monitoring was achieved with the same professional-level accuracy [123]. The main advantages of the CNN and DNN methods are both robustness and precision if trained with sufficient training data, and become more attractive when combined with wearable sensors for health monitoring.

8. Conclusions and perspectives

In this chapter, we have covered two major aspects: the importance of breath monitoring as a prevention method for early detection of several diseases; and the most recent achievements in hybrid material science, enabling the development of new noninvasive and flexible wearable sensors for breath monitoring. We have reviewed the working principle of these sensors with the requirements needed for industrial and clinical acceptance. When the functionality of fibers is augmented through a combination of chemical processes, their integration into fabric give arise to a new platform for wearable sensors called smart textile. The examples presented in this chapter illustrate the recent applications based on smart textile for breath monitoring in which the fabric is enriched with new functionalities while maintaining the mechanical properties and the comfort of the user. Wireless communication using smart textile based on multi-material fiber antenna is the most recent achievement in technological development in which the capability for RF emission at 2.45 GHz and monitoring breath in real time is assured by new generation fiber antennas. The advantages of such a technology are its endurance to the environmental changes and the reliability of the measurements. At this stage, the potential use of smart textile technology has not yet fully explored. We believe that future research will be focused on developing highly flexible materials sensitive to electrical, chemical, and physical changes with high endurance to the environmental conditions, capable to integrate textile for health-care monitoring. At this level, it will be important to develop alternatives for the powering, communication, and signal processing of such systems, in particular if someone would like to deploy such technology in the northern regions. Improving the power efficiency generated through thermoelectric, piezoelectric, and photoelectric effects could pave the road for new powerless system. Machine learning methods have shown lot of success on predicting events with up to 96% of sensitivity. This method could be of an important use for data processing and extraction of biopotential and vital signs.

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Chapter 16

An Evolutionary Perspective for Network Centric Therapy through Wearable and Wireless Systems for Reflex, Gait, and Movement Disorder Assessment with Machine Learning

Robert LeMoyne and Timothy Mastroianni

Abstract

Wearable and wireless systems have progressively evolved to achieve the capabilities of Network Centric Therapy. Network Centric Therapy comprises the application of wearable and wireless inertial sensors for the quantification of human movement, such as reflex response, gait, and movement disorders, with machine learning classification representing advanced diagnostics. With wireless access to a functional Cloud computing environment Network Centric Therapy enables subjects to be evaluated at any location of choice with Internet connectivity and expert medical post-processing resources situated anywhere in the world. The evolutionary origins leading to the presence of Network Centric Therapy are detailed. With the historical perspective and state of the art presented, future concepts are addressed.

Keywords: wearable systems, wireless systems, accelerometers, gyroscopes, smartphones, portable media devices, machine learning, reflex, gait, movement disorder

1. Introduction

Quantifying human movement characteristics can provide a significant foundation for enabling optimized rehabilitation therapy, for which the advent of wearable and wireless inertial sensor systems provides considerable opportunity [1–12]. The quantification of inertial sensor systems have been proposed for the measurement and quantification of human movement characteristics since approximately the mid-20th century. However, sufficient miniaturization and reliability regarding that timeframe had not been achieved for associated biomedical applications [11–15]. Motivating research, development, testing, and evaluation for the evolution of inertial sensors derived from industries extrinsic relative to the biomedical field, such as the automotive industry for regulation of airbag deployment [11–13, 15]. Upon the achievement of a sufficient threshold for miniaturization and reliability these inertial sensors have been successfully applied to numerous human movement scenarios, such as the quantification of reflex, gait, and movement disorder. Furthermore, these inertial sensors were noted as functionally wearable with wireless in capability, which ushered the presence of wearable and wireless inertial sensor systems for quantifying human movement [1–12]. A historical and evolutionary perspective leading to the amalgamation of inertial sensors that are functionally wearable with wireless connectivity to Cloud computing resources in conjunction with machine learning classification as an advanced post-processing technique, which is known as Network Centric Therapy, for the biomedical domain is presented.

2. Ordinal methodologies for quantifying reflex response, gait, and movement disorder

Prior to the advent of wearable and wireless inertial sensor systems, the diagnosis of a subject's health status was essentially derived from the expert although subjective interpretation of a skilled clinician. The clinician is generally tasked with the responsibility to interpret the health of the patient and apply the observation to an ordinal scale criteria methodology. This ordinal scale process is ubiquitous to the clinical domain, and this approach is relevant to the scope of reflex response, gait, and movement disorder. However, the ordinal scale strategy encompasses contention regarding reliability, and there generally does not exist a means for translating between various available ordinal scales [1, 3, 11, 12, 16–30].

Further issues with the ordinal scale approach are evident with respect to the imperative need for patient-clinician interaction. From a logistical perspective a patient is required to travel to a clinical appointment, which in the case of a specialized expert may require relatively long-distance travel. Additionally, the clinician is only provided with a short duration of time to interpret the patient's health status, which may be in dispute to the true health condition of the patient. The ordinal scale approach intuitively only provides limited insight of patient health, for which sensor signal data may provide a more revealing historical perspective.

3. Electro-mechanical systems providing signal data for quantifying reflex response, gait, and movement disorder

The acquisition of quantified sensor signal data enables more pertinent clinical acuity regarding the health status with respect to reflex response, gait, and movement disorder [1–12]. With respect to the quantification of reflex response an assortment of electro-mechanical sensor systems have been proposed. These devices generally have consisted of the means for evoking the reflex through a provisional reflex hammer and quantifying the correlated reflex response [17, 18, 31–38]. By temporally synchronizing the input quantification device eliciting the reflex and output quantification sensor of the reflex response a functional reflex latency can be derived [17, 18, 39, 40].

The quantification of the input that commences the reflex has been demonstrated through instrumented provisional reflex hammers and motorized devices. These devices enable measuring of the intensity of the eliciting impact and the time stamp regarding the start of the reflex respective of the neurological pathway. The reflex response, such as deriving from the patellar tendon, can be measured through electromyograms (EMGs), strain gauges, optical motion cameras, force sensors, and wired inertial sensors in addition to the associated time stamp. The temporal differential between the evoking reflex input time stamp and the reflex response time stamp can derive a functional latency of the reflex under consideration, such as the latency of the patellar tendon reflex [17, 18, 31–44].

Electro-mechanical systems have been applied for the quantified assessment of gait, which also pertains to movement disorder conditions. Representative electro-mechanical apparatus for quantifying gait consist of EMGs, optical motion cameras, force plates, foot switches, electrogoniometers, and metabolic analysis devices. These devices are generally reserved for clinical gait laboratories and imply supervision from expert clinical resources [11, 12, 45–48].

The acquired sensor signal data can be post-processed and applied to sophisticated techniques, such as machine learning, for distinguishing between various states of health during gait. Two particular types sensor signal are the force plate and optical motion camera [49–54]. The force plate provides kinetic signal data, and the optical motion camera provides kinematic signal data. The force plate and optical motion camera can be operated in tandem and synchronicity to derive clinically significant information about gait, such as ankle torque derived during stance [48].

These electro-mechanical systems enable quantification of human movement features, such as reflex response, gait, and movement disorders, through the acquired sensor signal data [31–38, 41–54]. Although these electro-mechanical systems are clinically standard, they are generally constrained to a clinical laboratory. Furthermore, the majority of these devices both require specialized resources for their experimental operation, and they are predominantly not portable [1–4, 6–12, 47, 48].

By contrast, the functionally wearable with wireless inertial sensor system considerably alleviates the constraints of specialized resources through simplified means of activating the inertial sensor signal recording. These devices constitute portable systems, and they are functionally wearable [1–12]. The origins of the advent of Network Centric Therapy commence with the research, development, testing, and evaluation for quantifying reflex response and latency, which subsequently lead to the extrapolation to the domains of wearable and wireless inertial sensors for gait and movement disorder quantification.

4. Evolutionary pathway for Network Centric Therapy with respect to quantification of reflex response and latency

The global evolutionary pathway for Network Centric Therapy derives from the Ph.D. Dissertation research conducted by Dr. LeMoyne, which lead to the progressive development of a device known as the Wireless Quantified Reflex Device through the incremental develop of four generations. The preliminary success involved the quantification of reflex response through locally wireless accelerometers. In order to measure the response of the patellar tendon reflex, the wireless accelerometers were mounted proximal to the lateral malleolus, which signified their wearable capability [17, 18, 40].

The original wireless accelerometers were provided through internal UCLA research, and they were referred to as MedNodes. The MedNodes required specialized operation, as they were the scope of graduate-level research at UCLA. These wireless accelerometer nodes that were noted as conveniently wearable were applied to the first and second generations of the Wireless Quantified Reflex Device, and the quantification of the patellar tendon reflex was measured in an accurate and reliable manner. The collected signal data of the wireless accelerometer was transmitted to a locally situated computer for post-processing [55, 56]. Central to all four generations of the Wireless Quantified Reflex Device was the integration of a quantified potential energy impact pendulum to consistently evoke the patellar tendon reflex [17, 18, 39, 40, 55, 56].

The third and fourth generations of the Wireless Quantified Reflex Device included a second wireless accelerometer to determine the time of impact for the quantified potential energy impact pendulum. The first wireless accelerometer was mounted to the ankle to quantify reflex response and time of response. Using the temporal offset of the wireless accelerometer mounted on the impact pendulum evoking the patellar tendon reflex and the wireless accelerometer mounted about the lateral malleolus mounted about the ankle to measure reflex response, a functional patellar tendon reflex latency was derived. The third and fourth generations of the Wireless Quantified Reflex Device incorporated the G-link wireless accelerometer developed by Microstrain [17, 18, 39, 40].

The third generation Wireless Quantified Reflex Device utilized streaming signal data to the locally situated portable computer for acquisition of the accelerometer signal data and subsequent post-processing. The third generation Wireless Quantified Reflex Device was the first evolution to feature the ability to derive functional reflex latency through the tandem wireless accelerometers with one wireless accelerometer located on the potential energy impact pendulum that evokes the patellar tendon reflex and the other wireless accelerometer mounted proximal to the lateral malleolus of the ankle for also acquiring reflex response. The research findings demonstrated that patellar tendon reflex response and associated functional latency could be both quantified with considerable accuracy and reliability [39].

The observations of the third generation Wireless Quantified Reflex Device established opportunity for improvement, such as increasing the sampling rate for the tandem accelerometers. This improvement would implicate better acuity with respect to the derived functional latency of the patellar tendon reflex. An artificial reflex device was applied as intermediary before the development of the fourth generation Wireless Quantified Reflex Device. This intermediary device utilized the data logger of the G-link wireless accelerometers, which permitted augmented sampling rates, while retaining wireless connectivity to a local portable computer for accelerometer signal data downloading and post-processing [57–59].

The fourth generation Wireless Quantified Reflex Device successful applied a longitudinal study for multiple subjects. With the wireless accelerometer set to data logger configuration with subsequent wireless transmission, the Wireless Quantified Reflex Device successfully acquired patellar tendon reflex response and functional latency with considerable accuracy, reliability, and reproducibility [40]. Subsequent evolutions encompass the application of more robust wearable and wireless inertial sensor systems and conjunction with machine learning to distinguish a hemiplegic reflex pair regarding affected patellar tendon reflex and associated unaffected patellar tendon reflex [60–62].

The next improvement incorporated the use of the portable media device and smartphone for the quantification of reflex response as a functional wireless accelerometer platform using the potential energy impact pendulum to evoke the patellar tendon reflex [63, 64]. The portable media device was suited for facilities with local wireless internet zones [63]. For locations requiring broad telecommunication access, the smartphone provides better benefit [64]. Both applications feature a common software application that enables a discrete recording of the accelerometer signal for quantifying the reflex response, and the signal data can be attached to an email for wireless transmission to the Internet for post-processing anywhere in the world [63, 64].

For example, LeMoyne and Mastroianni conducted an experiment to quantify reflex response using a portable media device applying supramaximal stimulation of the patellar tendon reflex in Lhasa, Tibet of China. The signal data was wirelessly transmitted to the Internet as an email attachment, which served as a provisional

Cloud computing resource. The data was later downloaded in Flagstaff, Arizona of the United States of America, which is effectively on the other side of the world, for post-processing [65].

Further advancements of the concept of quantifying reflex response, such as the patellar tendon, pertained to using the accelerometer signal, such as through a portable media device, to differentiate between a hemiplegic reflex pair. The hemiplegic affected leg's patellar tendon reflex response is notably more amplified relative to the patellar tendon reflex response of the unaffected leg. By consolidating the respective accelerometer signals to a feature set for machine learning classification using the support vector machine available through the Waikato Environment for Knowledge Analysis (WEKA) considerable machine learning classification accuracy was attained [60]. This achievement is notable, since subjective clinical observations to distinguish between a hemiplegic reflex pair is a matter of contention [21].

The gyroscope was eventually incorporated in the inertial sensor package of portable media devices and smartphones. The gyroscope provides a clinical representation for rotational characteristics of a joint, which represents the response of the patellar tendon reflex. Successfully demonstration of the gyroscope to quantify the patellar tendon reflex was demonstrated in the context of the Wireless Quantified Reflex Device through the potential energy impact pendulum [61, 62, 66–68].

Using both the potential energy impact pendulum and supramaximal stimulation to evoke the patellar tendon reflex response multiple machine learning algorithms using WEKA have achieved considerable classification accuracy [60–62, 66, 67]. **Figures 1** and **2** represent the gyroscope signal for the reflex response of the hemiplegic affected leg and unaffected leg, respectively. Machine learning algorithms, such as the J48 decision tree, provide a visualized basis for the most prevalent numeric attributes to establish classification accuracy, such as the time disparity between maximum and minimum angular rate of rotation for the patellar tendon reflex response, as illustrated in **Figure 3** [67].

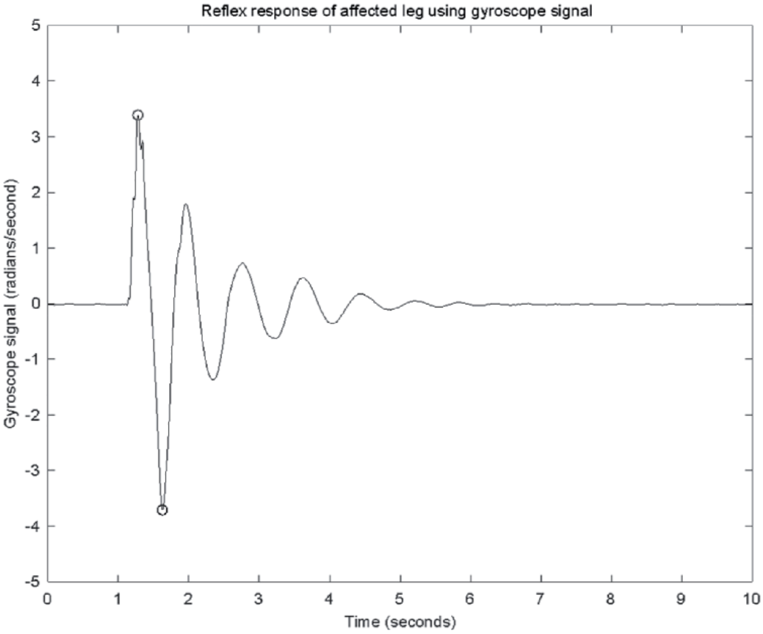

Figure 1.
The gyroscope signal of the patellar tendon reflex response for the hemiplegic affected leg using the potential energy impact pendulum to evoke the reflex [67].

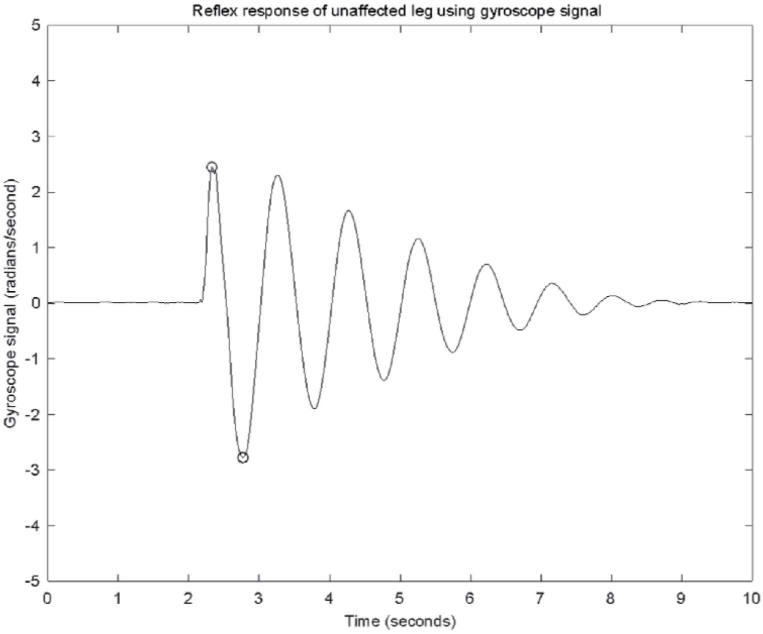

Figure 2.
The gyroscope signal of the patellar tendon reflex response for the unaffected leg using the potential energy impact pendulum to evoke the reflex [67].

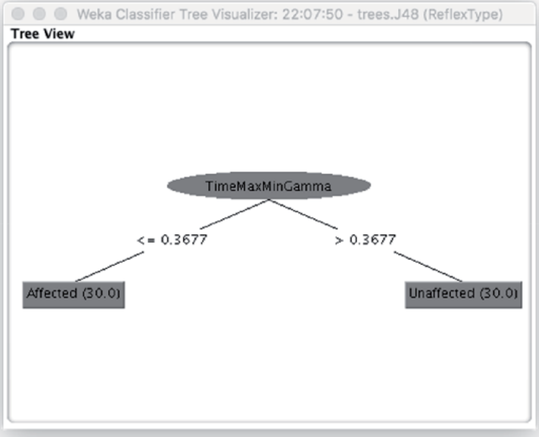

Figure 3.
The J48 decision tree to distinguish between a hemiplegic affected leg and unaffected leg, for which the time disparity between maximum and minimum angular rate of rotation for the patellar tendon reflex response numeric attribute is illustrated as the most prevalent for establishing classification accuracy [67].

5. Lessons learned through the research, test, and evaluation of the Wireless Quantified Reflex Device for the broader evolution of Network Centric Therapy, such as gait and movement disorder quantification

A readily noted capability observed by LeMoyne and Mastroianni was that since the wireless accelerometer was functionally wearable for the quantification of reflex response through mounting about the lateral malleolus of the patellar tendon, likewise the same mounting procedure could be applied for quantifying gait patterns [11, 12, 17]. Alternative mounting configurations, such as the lateral epicondyle proximal to the knee, were also feasible for assessing gait in a quantified context [11]. Additionally, the smartphone and portable media device were suitable candidates to represent functionally wearable and wireless inertial sensor systems (both accelerometers and gyroscopes) for gait quantification and eventually machine learning classification [3–10]. These concepts were also applied to the quantification of movement disorders through the mounting of wearable and wireless inertial sensor systems about the dorsum of the hand [1, 2, 5–10].

6. Evolutionary pathway for Network Centric Therapy with respect to quantification of gait

Preliminary attempts to apply functionally wearable wireless accelerometers to measure gait characteristics consisted of segmented subsystems and in some cases complex mounting techniques exceeding the knowledge of the common user [69–72]. The highly miniaturized, portable, and non-intrusive nature of the G-link wireless accelerometer developed by Microstrain demonstrate its robust capability for quantifying gait characteristics [11]. Proof of concept from an engineering perspective was demonstrated for the identification of quantified disparity of hemiplegic gait and Virtual Proprioception to enable real-time rehabilitation of hemiplegic gait [73–76].

Preliminary research, development, testing, and evaluation by LeMoyne et al. applied the G-link Microstrain wireless accelerometer to ascertain quantified disparity of hemiplegic gait. The wireless accelerometer nodes were effectively wearable. They could be mounted about the lateral epicondyle proximal to the knee through an elastic band or about the lateral malleolus near the ankle using the elastic band of a sock [74, 75].

The wireless accelerometer achieved connectivity to a locally situated personal computer, which would then serve as the basis for post-processing. Using the acceleration magnitude of the three-dimensional orthogonal acceleration signal, characteristic spikes of the acceleration magnitude signal represented the initiation of stance. The time averaged acceleration from stance to stance enabled the quantification of gait characteristics [74, 75]. Furthermore, through the ratio of the hemiplegic affected leg to the unaffected leg using the time averaged acceleration from stance to stance, the quantified disparity of hemiplegic gait could be quantified with the potential for deriving therapeutic intervention for rehabilitation [74]. Functionally wearable and locally wireless accelerometers have also been applied to successfully contrast hemiplegic gait with respect to the frequency domain [73]. Other applications of wireless accelerometer systems that are functionally wearable have been successfully demonstrated for the context of effectively autonomous gait analysis based on quantified data derived from the acceleration signal [11, 12, 69–72].

Virtual Proprioception expanded the capabilities of functionally wearable wireless accelerometers for real-time modification of hemiplegic gait based on accelerometer signal data. The wireless accelerometers were mounted by flexible elastic bands proximal to the lateral epicondyle of the knee for both the unaffected leg and hemiplegic affected leg. Based on a visual feedback strategy the person with hemiplegic gait was able to modify the hemiplegic affected leg to a more representative acceleration signal representative of the unaffected leg [76].

During 2010 LeMoyne and Mastroianni sought to expand the availability of wearable and wireless accelerometer systems for quantifying gait in the context of more commercially available systems. The smartphone of that timeframe was equipped with an internal accelerometer. Additionally, the smartphone is inherently capable of wirelessly accessing the Internet. A software application for recording the accelerometer data for a prescribed duration and sampling rate with wireless transfer to the Internet as an email attachment enables the smartphone to function as a wearable and wireless inertial sensor system. The email resource represents a provisional representation of a Cloud computing resource. These characteristics enable the smartphone to quantify gait features in the context of a wearable and wireless inertial sensor system [77]. These preliminary capabilities constitute the origins of Network Centric Therapy for the domain of gait analysis [3–7, 78].

Preliminary testing and evaluation of the smartphone as a wearable and wireless inertial sensor system for gait analysis was conducted in region of Pittsburgh, Pennsylvania. The experimental gait analysis accelerometer data was conveyed wirelessly to the Internet as an email attachment for subsequent post-processing in the general area of Los Angeles, California. The implications were that experimental and post-processing locations could be geographically separated anywhere in the world with Internet connectivity [77].

The preliminary gait experiment of 2010 implementing the smartphone as a wearable and wireless inertial sensor system through the internal accelerometer involved mounting the smartphone proximal to the lateral malleolus of the ankle joint by an elastic band. Two primary gait characteristics were quantified, such as the temporal duration between stance to stance and time averaged acceleration from stance to stance. These parameters acquired by the smartphone functioning as a wearable and wireless inertial sensor system through the available accelerometer demonstrated considerable accuracy and reliability [77].

Additional and similar themed experiments pertained to quantification of gait through other mounting applications, which underscores the flexibility of the smartphone as a wearable and wireless inertial sensor system. The two other mounting positions involved the lateral epicondyle near the knee joint and lumbar-sacral aspect of the spine through an elastic band. The temporal duration between stance to stance cycle displayed considerable accuracy and reliability and successfully elucidated predominant frequencies in the context of the frequency domain with respect to both mounting strategies [79, 80].

Another device that is similar to the smartphone for applications as a wearable and wireless inertial sensor system for the quantification of gait is the portable media device. The portable media device can utilize the same software application as relevant to the smartphone. Although the portable media device is generally restricted to an area with local internet connectivity, this device has a lighter mass and is more affordable for tandem applications involving both legs for gait analysis [3–10, 78].

Preliminary, testing of the portable media device was successfully demonstrated with mounting about the lateral malleolus of the leg by an elastic band. The accelerometer of the portable media device successfully quantified gait in an accurate and consistent manner. The experimental data was conveyed by wireless transmission through the Internet as an email attachment, and the experimental and post-processing resources were situated on opposite sides of the continental United States. Post-processing emphasized the derivation of step cycle time (stance to stance) and time averaged acceleration (stance to stance) [81].

An observation of the portable media device is that it is more affordable than the smartphone, such as for the application of two tandem operated portable media devices for quantifying the disparity of hemiplegic gait. LeMoyne and Mastroianni incorporated two portable media devices in the context of a wearable and wireless inertial sensor system, such as an accelerometer, for quantifying hemiplegic gait respective of the unaffected leg and the hemiplegic affected leg. The devices were mounted about the lateral malleolus of the ankle joint through an elastic band for both the unaffected leg and the hemiplegic affected leg. The tandem activated portable media devices successfully demonstrated the ability to quantitatively identify stance to stance temporal duration and stance to stance time averaged acceleration of the hemiplegic affected leg and unaffected leg with statistical significance. Also, the ratio of stance to stance time averaged acceleration less the offset for the hemiplegic affected leg and unaffected leg demonstrated quantified disparity [82].

Eventually a strategy for using a singular smartphone to quantify hemiplegic gait and its associated disparity was established with the incorporation of a treadmill to maintain constant velocity. The smartphone functioning as a wearable and wireless accelerometer platform was mounted about the lateral malleolus of the ankle by an elastic band. Automated post-processing software emphasized the rhythmic characteristics of gait and acquired gait parameters, such as stance to stance temporal disparity and stance to stance time averaged acceleration. The stance to stance temporal disparity did not display statistical significance, because of the treadmill velocity constraint. Statistical significance was achieved for stance to stance time averaged acceleration with respect to comparing the hemiplegic affected leg to the unaffected leg. This experimental configuration enables the evaluation and quantification of gait in an autonomous environment [83].

Evolutionary trends eventually enabled the smartphone to quantify gait through the internal gyroscope, which offers a more clinically representative kinematic signal. The strategy of conducting gait analysis constrained to a constant velocity by a treadmill was applied. A smartphone functioning as a wearable and wireless gyroscope platform quantified hemiplegic gait in terms of both the affected leg and unaffected leg with mounting about the lateral malleolus near the ankle joint through an elastic band. The gyroscope signal was consolidated to a feature set during the post-processing phase, which consisted of five numeric attributes: maximum, minimum, mean, standard deviation, and coefficient of variation. Using the multilayer perceptron neural network considerable classification accuracy was attained for distinguishing between the hemiplegic affected leg and unaffected leg during gait [84].

Additionally, the smartphone through its internal inertial sensor system has been applied to other applications pertaining to the domain of gait analysis and associated mobility. Smartphones have been successfully incorporated for augmenting the acuity of clinically standard evaluations, such as the Timed Up and Go and 6-Minute Walk Test [85–87]. An observed utility of the strategy of augmenting clinically standard evaluation techniques with functionally wearable and wireless inertial sensor systems, such as the smartphone, is the ability to evolve a clinical method rather than inventing a new methodology.

During this phase of the evolutionary process that lead to the realization of Network Centric Therapy a new observation occurred. Smartphones and portable media devices can function as representative and effective wearable and wireless inertial sensor systems. However, their evolutionary pathway is not consistent with the biomedical and healthcare domain. A new perspective for wearable and wireless inertial sensor systems was developed, which incorporated inertial sensor nodes with local wireless connectivity to a device, such as a smartphone or tablet, with considerably expanded wireless access to the Internet. This paradigm shift enabled considerable reduction in mass and volumetric profile for the wearable and wireless inertial sensor system. This strategy enabled segmented wireless access of the inertial signal data for connectivity to a Cloud computing resource [88].

During 2016 LeMoyne et al. utilized a wearable and wireless inertial sensor system architecture in the context of Network Centric Therapy for the evaluation of gait for subject's with Friedreich's ataxia. The system applied local wearable and wireless inertial sensor nodes with local wireless connectivity to a tablet with global wireless access to a Cloud computing environment. A multilayer perceptron neural network achieved considerable classification accuracy to distinguish between a person with healthy gait and gait for a person with Friedreich's ataxia [89].

The current state of the art for demonstrating the capability of Network Centric Therapy involves the recent test and evaluation of the BioStamp nPoint, which represents a conformal wearable and wireless inertial sensor system. The BioStamp nPoint achieves wireless connectivity for acquiring signal data for quantifying gait in a segmented manner through wireless systems, such as a tablet for operation and smartphone for Cloud computing access. **Figure 4** presents the supporting apparatus for the BioStamp nPoint conformal wearable and wireless inertial sensor system [90].

Recently, during 2020 LeMoyne and Mastroianni applied the BioStamp nPoint to quantify hemiplegic gait with distinction through machine learning. The BioStamp nPoint conformal wearable and wireless inertial sensor system was mounted by adhesive medium to both the hemiplegic affected leg and unaffected leg about the femur and proximal to the patella as shown in **Figure 5**. The subject walked on a treadmill for the experiment [91].

Figure 4.
The BioStamp nPoint conformal wearable and wireless inertial sensor system and supporting devices, such as docking station, tablet, and smartphone [90].

Figure 5.
The BioStamp nPoint conformal wearable and wireless inertial sensor system mounted about the femur for the quantification of hemiplegic gait [91].

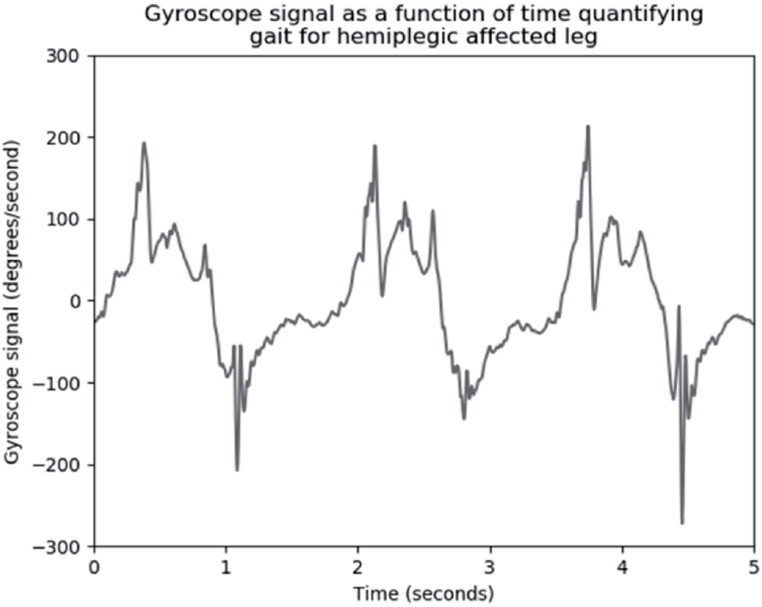

Figure 6.
The BioStamp nPoint conformal wearable and wireless inertial sensor signal for the hemiplegic affected leg [91].

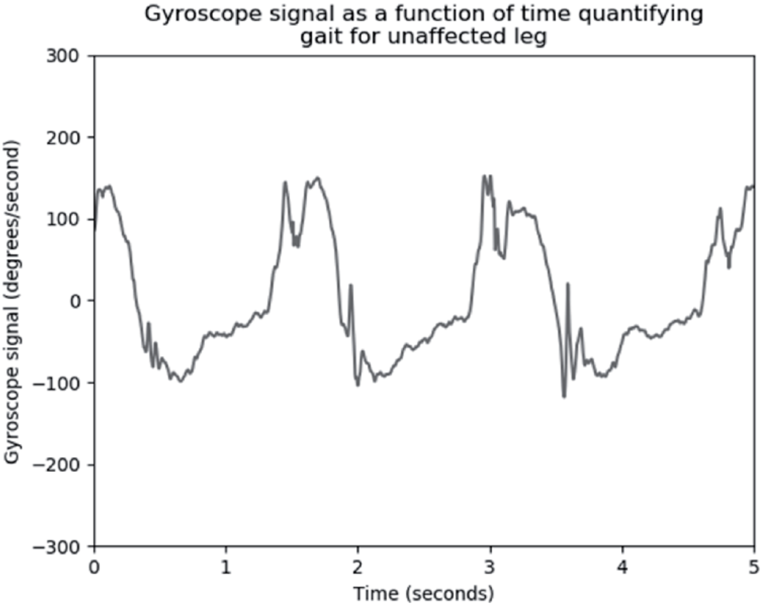

Figure 7.
The BioStamp nPoint conformal wearable and wireless inertial sensor signal for the unaffected leg [91].

The gyroscope signal revealed notable disparity respective of the affected leg and unaffected leg during gait as presented in **Figures 6** and 7 respectively. Post-processing of the gyroscope signal data consolidated a feature set consisting of five numeric attributes based on descriptive statistics, such as maximum, minimum, mean, standard deviation, and coefficient of variation. Multiple machine learning classification algorithms, such as the support vector machine and multilayer perceptron neural network, achieved considerable classification accuracy to distinguish between the hemiplegic affected leg and unaffected leg [91, 92].

7. Evolutionary pathway for Network Centric Therapy with respect to quantification of movement disorders, such as Parkinson's disease and Essential tremor

Functionally wearable accelerometer systems have been demonstrated for the quantification of movement disorder and also their response to intervention strategy [11, 12, 93–98]. With the evolution of wireless technology other traditional inertial signal data transfer strategies have become effectively obsolete [99]. Intuitively, the G-link wireless accelerometer was a candidate for testing and evaluating the quantification of tremor associated with movement disorders [11, 12, 100–103].

Preliminary demonstration of the G-link wireless accelerometer showed the ability to quantify simulated Parkinson's disease hand tremor by mounting the device to the dorsum of the hand [100, 101]. Eventually simulated Parkinson's disease tremor was contrasted to a static condition. Post-processing of the signal data involved the time averaged acceleration, for which statistical significance was achieved [100]. A similar wireless inertial sensor system configuration was successfully demonstrated for the quantification of Parkinson's disease hand tremor within this timeframe [104].

LeMoyne and Mastroianni during 2010 extended the capability of wearable and wireless inertial sensor systems for quantifying Parkinson disease hand tremor through the application of a smartphone. A software application enabled the smartphone to quantify hand tremor for a prescribed temporal duration through the smartphone's internal accelerometer. The accelerometer signal data was conveyed by wireless connectivity to the Internet as an email attachment. Statistical significance was achieved with respect to the subject with Parkinson's disease hand tremor and subject without Parkinson disease. Notably, the experiment occurred in metropolitan Pittsburgh, Pennsylvania and the post-processing was conducted in the general area of Los Angeles, California [105]. The research team observed that experimental and post-processing resources could be geographically separated anywhere in the world with Internet access [1, 2, 5–10, 105, 106]. This observation constitutes the origins of Network Centric Therapy with regards to movement disorders [1, 2, 5–7, 106].

Using the smartphone as an inertial sensor platform with wearable properties the recorded signal data can represent instrumental feedback with respect to the efficacy of therapy response. For example, with machine learning classification the smartphone functioning as a wearable and wireless inertial sensor platform can distinguish between deep brain stimulation set to 'On' and 'Off' status. A person with Essential tremor performed a reach and grasp task with a smartphone mounted to the dorsum of the hand by a latex glove. Post-processing consolidated the inertial signal data to a feature set amenable for machine learning classification, and considerable classification accuracy was achieved through the application of a support vector machine to differentiate between deep brain stimulation set to 'On' and 'Off' status [107]. In conjunction with the preliminary success of the research with respect to Essential tremor and deep brain stimulation set to 'On' and 'Off' status the multilayer perceptron neural network also attained considerable machine learning classification accuracy for differentiating these deep brain stimulation settings [108].

Another extrapolation of this research perspective involved considering six machine learning algorithms: multilayer perceptron neural network, support vector machine, K-nearest neighbors, logistic regression, J48 decision tree, and random forest. The reach and grasp task was applied for a subject with Essential tremor treated by deep brain stimulation with respect to 'On' and 'Off' status. Three feature set scenarios were addressed to determine the most appropriate machine learning algorithms: accelerometer and gyroscope signal recordings, accelerometer signal recordings, and gyroscope signal recordings. The multilayer perceptron neural network, support vector machine, K-nearest neighbors, and logistic regression achieved the highest classification accuracy in consideration of these three feature set scenarios [109].

The accelerometer and gyroscope intrinsic to the smartphone was also applied for the evaluation of deep brain stimulation efficacy for the treatment of Parkinson's disease. Deep brain stimulation was set to 'On' and 'Off' status with the hand tremor response measured by a smartphone mounted to the dorsum of the hand through a latex glove. Multiple machine learning algorithms were evaluated: multilayer perceptron neural network, support vector machine, K-nearest neighbors, logistic regression, J48 decision tree, and random forest. The feature set consisted of descriptive statistics for both the accelerometer and gyroscope signal data. Two performance parameters were considered, such as classification accuracy and time to develop the machine learning model. The support vector machine and logistic regression best satisfied these two performance parameters [110]. The multilayer perceptron neural network achieved considerable classification accuracy to distinguish between the deep brain stimulation set to 'On' and 'Off' status for Parkinson's disease hand tremor, but the time to develop the model was considerably protracted [110, 111].

Network Centric Therapy was further realized for the domain of movement disorders through the BioStamp nPoint. The BioStamp nPoint is a conformal wearable and wireless inertial sensor system with segmented operation and wireless transmission of signal data to a secure Cloud computing environment with wireless connectivity to a smartphone and tablet. The conformal sensors also have a mass less than ten grams and a profile on the order of a bandage. Additionally, the BioStamp nPoint is certified as an FDA 510(k) medical device for the acquisition of medical grade data [5, 90]. These attributes of the BioStamp nPoint ideally accommodate the quantification of movement disorder tremor response, such as for Parkinson's disease, based on deep brain stimulation intervention through mounting about the dorsum of the hand using an adhesive medium as illustrated in **Figure 8** [112].

Multiple sets of deep brain stimulation parameter configurations have been evaluated for the treatment of Parkinson's disease using the BioStamp nPoint to quantify the response and machine learning to distinguish the respective parameter configurations [112–115]. The BioStamp nPoint was mounted to the dorsum of

Figure 8.
The BioStamp nPoint conformal wearable and wireless inertial sensor system mounted about the dorsum of the hand for quantifying movement disorder tremor response, such as for Parkinson's disease, as a result of deep brain stimulation intervention [112].

the hand through an adhesive medium. The deep brain stimulation amplitude was evaluated at multiple settings, such as 'Off' status as a baseline, amplitude set to 1.0 mA, 2.5 mA, and 4.0 mA. The acceleration signal derived from the BioStamp nPoint conformal wearable and wireless inertial sensor system was post-processed to present the acceleration magnitude as illustrated in **Figures 9–12** [112].

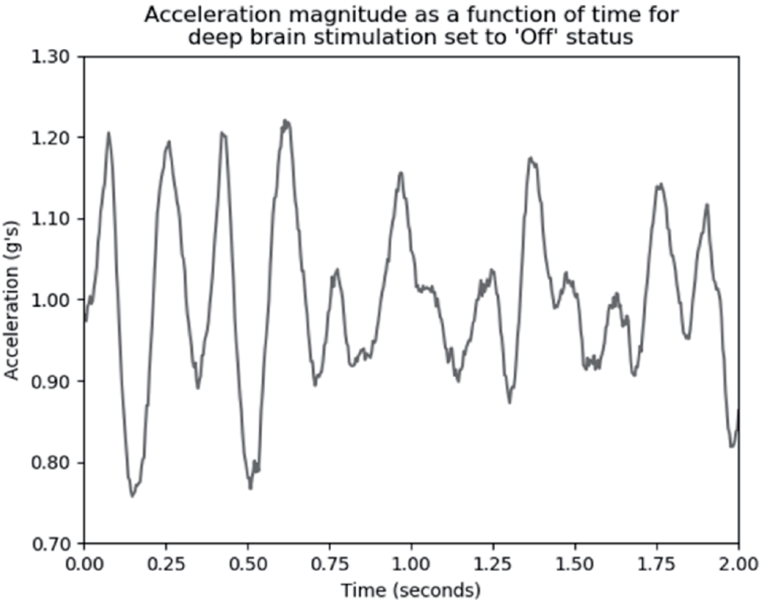

Figure 9.
Acceleration magnitude derived from the BioStamp nPoint conformal wearable and wireless inertial sensor system for hand tremor from a subject with Parkinson's disease with deep brain stimulation set to 'Off' status [112].

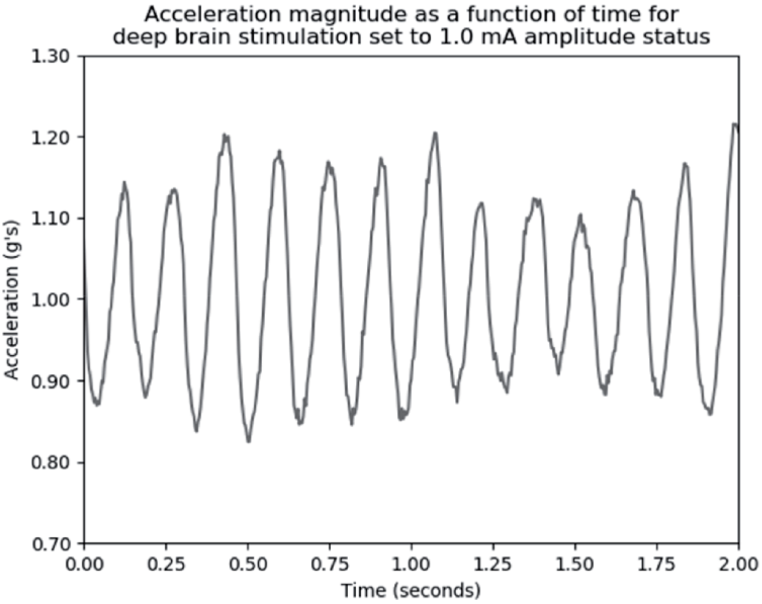

Figure 10.
Acceleration magnitude derived from the BioStamp nPoint conformal wearable and wireless inertial sensor system for hand tremor from a subject with Parkinson's disease with deep brain stimulation set to amplitude equal to 1.0 mA [112].

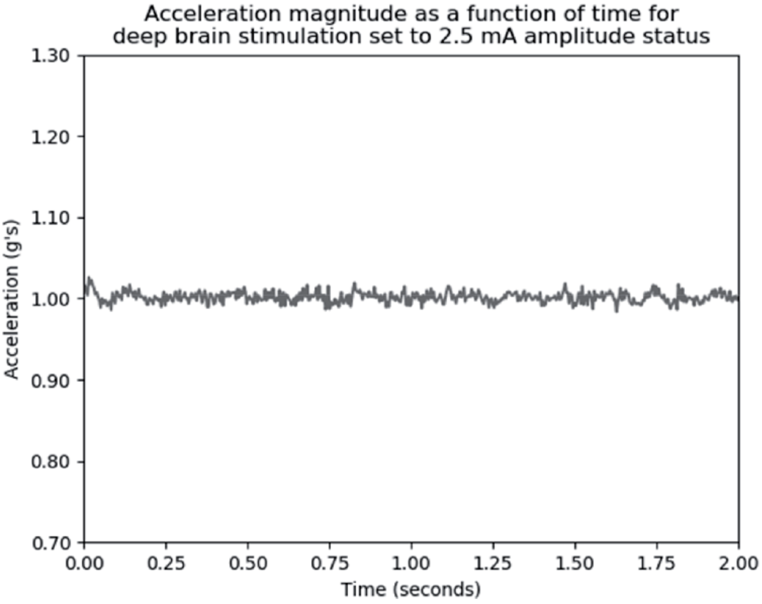

Figure 11.
Acceleration magnitude derived from the BioStamp nPoint conformal wearable and wireless inertial sensor system for hand tremor from a subject with Parkinson's disease with deep brain stimulation set to amplitude equal to 2.5 mA [112].

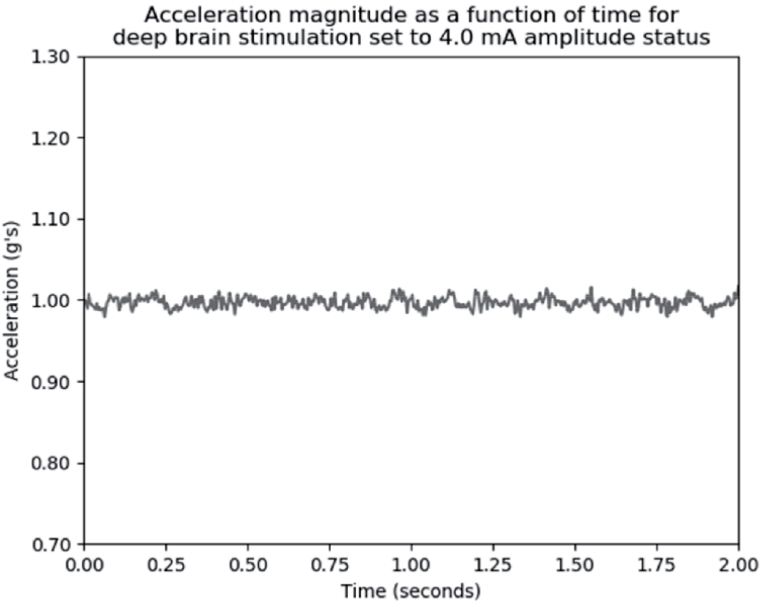

Figure 12.
Acceleration magnitude derived from the BioStamp nPoint conformal wearable and wireless inertial sensor system for hand tremor from a subject with Parkinson's disease with deep brain stimulation set to amplitude equal to 4.0 mA [112].

The acceleration magnitude signal data was consolidated to a feature set though Python. The feature set was composed of numeric attributes, such as maximum, minimum, mean, standard deviation, and coefficient of variation. Machine learning algorithms, such as J48 decision tree, K-nearest neighbors, support vector machine, logistic regression, and random forest were contrasted in terms of their classification accuracy and time to develop the machine learning model. Based on these criteria the K-nearest neighbors machine learning algorithm displayed the optimal satisfaction of classification accuracy in conjunction with time to develop the machine learning model and the support vector machine achieved the optimal classification accuracy [112]. The multilayer perceptron neural network also demonstrated considerable classification accuracy [113].

Deep learning was then applied to distinguish between deep brain stimulation parameter configuration settings for the treatment of Parkinson's disease, such as 'Off' status as a baseline, amplitude set to 1.0 mA, amplitude set to 1.75 mA, amplitude set to 2.5 mA, amplitude set to 3.25 mA, and amplitude set to 4.0 mA. The BioStamp nPoint conformal wearable and wireless inertial sensor system provided the accelerometer signal data. The post-processing was facilitated by Google Colab and TensorFlow to implement a convolutional neural network. The convolutional neural network achieved considerable classification accuracy to distinguish between all six of these parameter configurations [116, 117].

8. Future perspectives for Network Centric Therapy for reflex, gait, and movement disorder assessment with machine learning

Network Centric Therapy is anticipated to have a transformative influence on the healthcare and biomedical industry. Conformal wearable and wireless inertial sensor systems are envisioned to enable historical and distinctly quantified data for subjects undergoing rehabilitation and subjects with neurodegenerative movement disorders, such as Parkinson's disease and Essential tremor. Data science methodologies can be incorporated to optimize the respective therapy strategy. With the amalgamation of machine learning and eventually deep learning conformal wearable and wireless inertial sensor systems are predicted to considerably advance augmented clinical situational awareness for diagnostic and prognostic capabilities. In particular, with the Cloud computing accessibility intrinsic to Network Centric Therapy, the most talented clinical resources from anywhere in the world can provide optimal patient specific rehabilitation and therapy to subjects from the convenience of a homebound setting. Additionally, the inherent aspects of Network Centric Therapy, such as conformal wearable and wireless inertial sensor systems, machine learning, and Cloud computing access, imply a plausible pathway to the closed-loop optimization of deep brain stimulation parameter configurations.

9. Conclusion

The evolutionary perspective for the advent of Network Centric Therapy for the domains of assessing reflex, gait, and movement disorders have been thoroughly discussed. Inherent aspects pertaining to Network Centric Therapy involve wearable and wireless inertial sensor systems, machine learning, and Cloud computing access for the acquired inertial sensor signal data. The implications are that expert clinicians can access a patient's health status based on the wearable and wireless inertial sensor system signal data from anywhere in the world. These achievements constitute a significant evolution relative to traditional ordinal scale methodologies and electro-mechanical signal data obtained by clinical laboratory resources. Conformal wearable and wireless inertial sensor systems have further evolved the capabilities of Network Centric Therapy. In the future Network Centric Therapy is envisioned to augment clinical diagnostic and prognostic acuity, optimize rehabilitation, and enable closed-loop optimization of deep brain stimulation parameter configurations.

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Chapter 17

Challenges of WSNs in IoT

Brijesh Kundaliya

Abstract

IoT and WSNs are the prime moving force for technology in the current world. WSNs unfold their capacity day by day in almost every aspect of life. IoT enables to integrate the different devices and makes it possible to communicate with each other. It makes life easier and upgrades the application's usage to the next level. The integration of WSNs with IoT will help to reach apical of the usage of applications. The combination of WSNs and IoT will open up new doors in almost all the possible fields however the amalgamation of both the technology needs careful consideration about bringing the both on same level. The IoT is considered a mighty giant with enormous power and capability. On the other side, WSNs are miniature having limited resources but the tremendous capability to penetrate in almost every aspect of life. WSN's limited resources are the main concern while integrating it with the IoT. The integration will make it possible to access the sensor node from any part of the world. It implies that now the sensor node is open for any heterogeneous internet user in the world. It will cause a security issue. Moreover, the topology and addressing of WSNs are different from the normal internet which needs to be addressed during the integrations. And there are other challenges too which we discussed in depth in this chapter.

Keywords: WSNs, IoT, integration, security, addressing

1. Introduction

Wireless Sensor Networks (WSNs) will be the dominating field in the future era. Right now it is in the transformation phase [1]. It unfolds its capacity and is sorting out its limitations. CISCO is a giant player in the networking field. According to CISCO, the number of devices connected to the internet will be around 50 billion by 2021 which is shown in **Figure 1**. We will be surrounded by the sensors, rather on a lighter note, we can say that we will be captured by the sensors. The sensor networks will generate more than 500 zettabytes of data, which may be structured or unstructured data (Cisco Press release, 2018). The WSNs market was valued at USD 46.76 billion and expected that it will reach USD 123.93 by 2025 as depicted in **Figure 2**. The application range of the wireless sensor network is broad, from simple house automation to emergency response robots for forest fire detection.

The number of devices connected with the internet creates the network of the device which enables the controlling of a physical quantity (i.e. room temperature, fan speed, etc. …) remotely through the internet. This is nothing but the IoT. WSNs and IoT go hand to hand with small differences. So let's first understand the relationship between IoT and the WSNs. If we consider the tree as IoT then the leaf of the tree is the WSNs. WSNs architecture consist of sensor nodes and a sink node as shown in **Figure 3**. The sensor node has to perform two operations: sensing the physical quantity and forward the sensed data. In other words, it has to play two

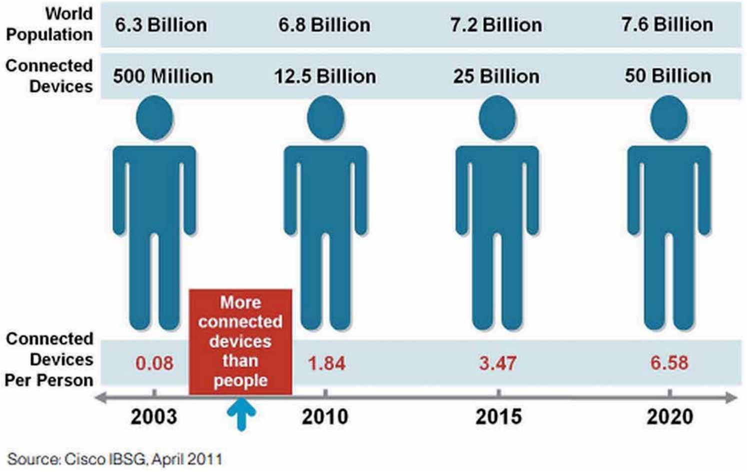

Figure 1.
Number of devices connected to internet (Cisco Press release) [2].

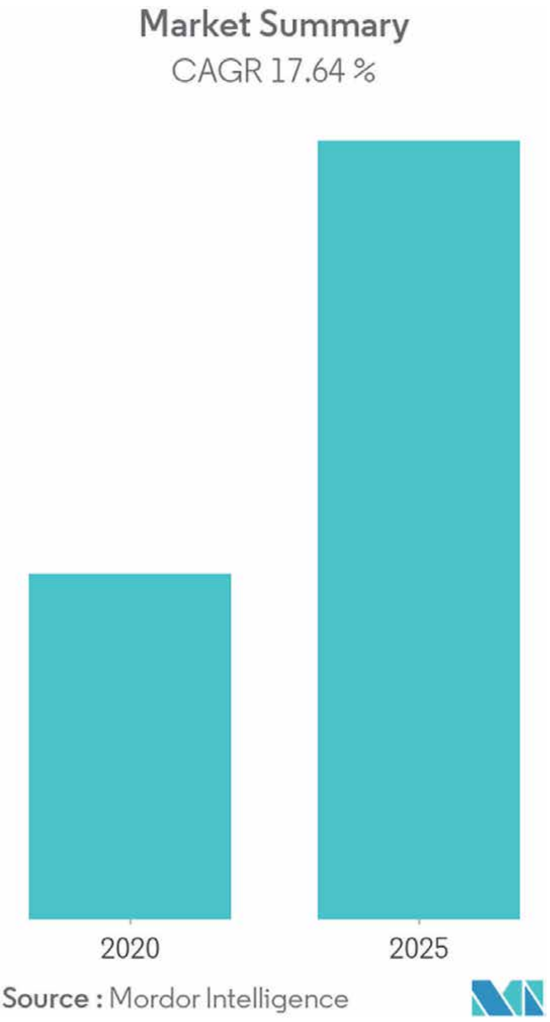

Figure 2.
Market growths of WSNs (ETNO) [2].

roles, as data generating and data forwarding. IoT works at a higher level, which integrate WSNs, any physical object connected to the internet, Internet, Apps, cloud computing, etc. as shown in **Figure 4**. We can say that WSNs can be considered as the subpart of the WSNs as shown in **Figure 5**.

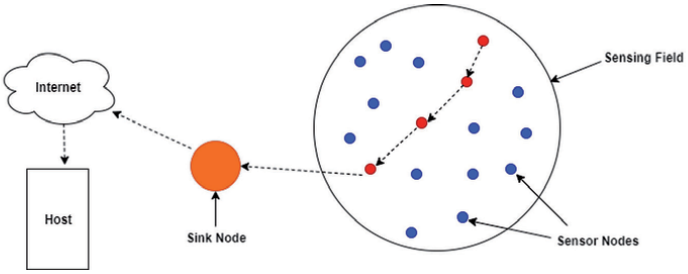

Figure 3.
WSNs architecture.

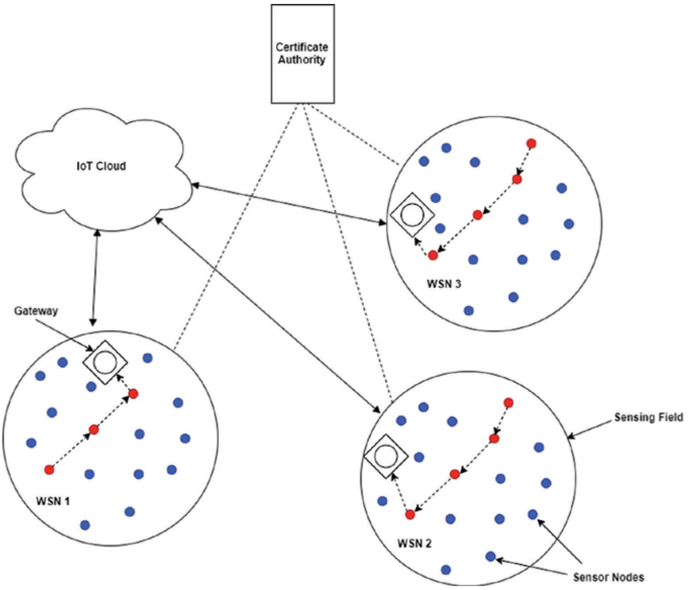

Figure 4.
IoT architecture.

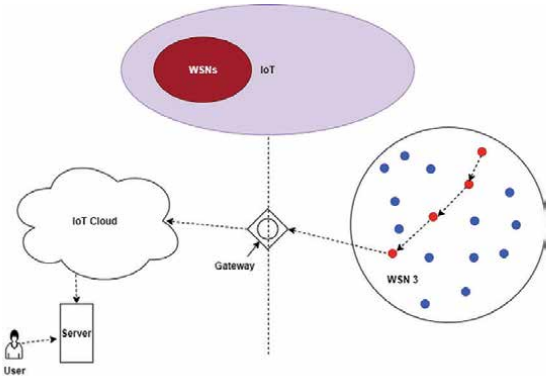

Figure 5.
Interrelation between IoT and WSNs.

2. Integrations and challenges

The integration of the WSNs with the IoT opens the ajar door of applications in every aspect of life. We are aware that in WSNs, the sensor comes with limited capacity in terms of memory, processor, and power, whereas IoT is equipped with abundant resources. It is very much important that the merging of WSNs with the IoT has to be done in a way that they maintain their authentic functions while helping each other to enrich the application ranges [3]. There are certain issues with this integration that is discussed in the following section.

2.1 Connectivity and infrastructure

The first step for integration is the connection of WSNs with the internet. There are three different way by which WSNs is connected with the internet [4]. The first approach is the Front-end proxy solution, in which the base station works as the interface between the sensor nodes and the internet. The base station is the main controlling element that can gather the information from the sensor node or can send any control information to sensor nodes. The base station worked as an insulator between the sensor node and the internet. The Sensor node is completely autonomous that gives the privilege to implements its algorithms and protocol. As shown in the **Figure 6** it is the base station responsibility to map the data of sensor node to equivalent internet protocol and vice versa. Base station has the capability to handle data coming from the internet having TCP/IP compatibility as well as data coming from the sensor node having the format of special sensor network protocol. It also has the capability to communicate with MAC layer as well as IEEE 802.15.4 (wireless standard) [5].

The second approach is the gate-way solution, where a base station serves as the application layer gateway. Here the Base station commands the lower layers of the internet as well as the WSNs. In this approach, WSNs can maintain their individuality at a certain level but still, it is compulsory to create the table, which maps sensor node address to IP address. As we can see in **Figure 7** at base station, sensor data can maintain its individuality up to TCP/IP layer only. At above layer data will be treated as common one.

The third solution is the TCP-IP overlay solution, where the sensor node can directly communicate with the internet using TCP-IP protocol. The base station is worked as a router that connects the two networks. In this approach, the node must need to implement the algorithm and protocol used in the internets. It offers the holistic integration of the WSNs with the internet. It is very much clear form the **Figure 8** that, sensor node must have installed TCP/IP protocol. In this solution, up

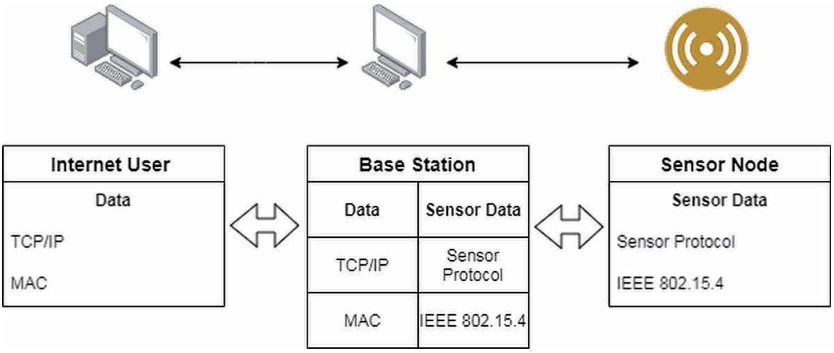

Figure 6.
Front end proxy solution.

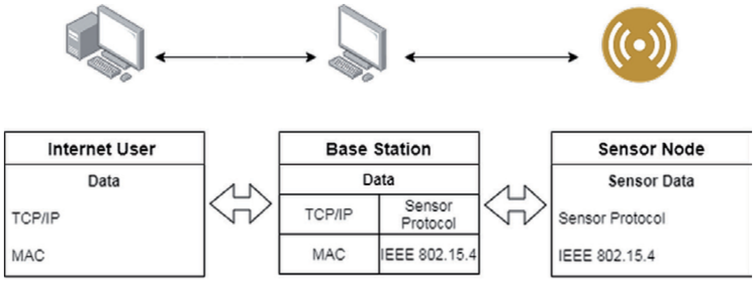

Figure 7.
Gateway solution.

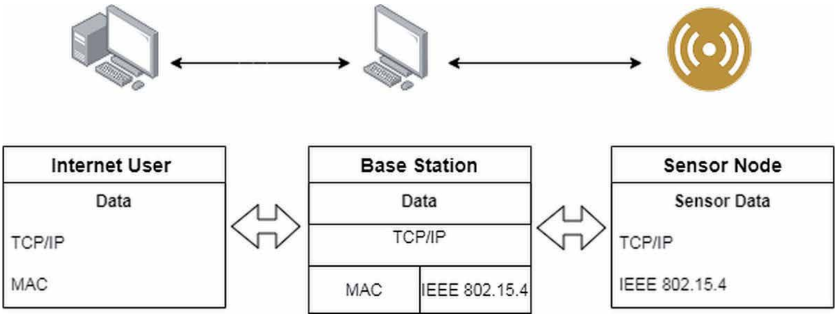

Figure 8.
TCP/IP overlay solution.

to MAC layer the WSNs can maintain its uniqueness after that there is no difference between WSNs data and IoT data.

When we connect the sensor nodes to the internet it certainly enhances the application range and quality. But it is still not clear that up to which extent we need to allow that integration. If we keep the sensor node isolated from the internet that narrows down the capacity of IoT and WSNs. On the other hand, if we go for full integration it is quite difficult for the sensor node to handle the communication with limited resources. There are certain aspects that need to be answered for full integration.

2.2 Addressing

In a front-end proxy solution, the base station needs to have the capability to enable interoperability between WSNs and the Internet. In the second case, the base station has to perform the task of an application layer gateway. It needs to be compatible with internet protocol as well as the WSNs protocol. In the third approach where the node can directly connect with the internet, means the sensor node needs to have direct IP addresses. It is indeed difficult to run standard internet protocol on to the sensor node having limited resources due to following reasons.

i. Deployment: In internet devices are consider as fixed entity. Their physical location remains unchanged throughout the operation. Network administrator is well aware about the topology which is normally remaining fixed. In WSNs the sensor node deployed in the random manner in sensing field. Moreover, in many applications mobile sensor nodes are used. It implies that topology of sensor node are continuously changing.

ii. Vulnerability: Sensors are placed in the event prone area. It is possible that during the operation it might get damage due to any reason and leads to dead node. Moreover, excessive events results in excessive communication that causes excessive energy consumption at the node.

iii. Limited Resources: Sensor node has a limited energy. To enhance the energy utilization it continually changes its states from active mode to sleep mode and vice versa. In sleep mode the sensor node is virtually out of the network which directly affects it topology.

It is very much clear that the addressing of WSNs and IoT is quite different. It is niche factor that decide the faithful operation of the WSNs and IoT's integration. It is utter most important to keep an eye on the topology change of WSNs [6–8].

2.3 Protocols

WSNs is designed for specific applications. Its protocols are tailored according to the specific requirements of the application and surrounding of the event area. Protocols are designed in such a way that it uses minimum information from the network to complete the task. The limited processing capacity and the energy of the node are the reason behind this. On the other side the IoT have the unlimited processing capacity and able to spend more energy in the communication. IoT deals with more broad aspect of applications and hence its protocol must be designed in such a way that it addresses the general aspects [9]. Integrating application specific protocol with the general protocol needs careful approach so that it maintains their endemic operation as well as the interoperability [1, 10].

2.4 Node and data availability

The core focus of WSNs is sensory data. It depends on the availability of the sensor node. WSNs are equipped with fewer resources especially power. To reduce the power usage, the node continuously switches to sleep mode from the active node and vice versa. In the worst situation, due to excessive usage of power node becomes dead. It implies that a particular part of the network is out of range. The sleeping node and dead node are not able to send the data and out of the topology. While we integrating the WSNs with the internet, the external host may not able to collect the data from the node due to the unavailability of the node. In addition to that, a malicious external host can attack a node in several ways i.e. generating the false or dummy data and saturate the node resources like a battery. So it is inevitable to devise a way that can assure the availability node and data correctly.

The mobility of the node in the sensor network is also an essential issue to be dealt with carefully. In many applications, the sensor nodes are continuously changing its position to collect the data. Moreover, WSNs also comes with a new data collecting approach called the mobile sink node. In that, the sink node travels through the network on a specified path to collect the data from the sensor nodes. Here the topology is continuously changed with the time which needs to be handling precisely while integrating with the internet [11].

2.5 Hardware and technological issue

A wireless sensor network is meant for specific applications. The sensor node has to provide specific data for as long as possible time with minimum resources. They use the low data rate communication to save the energy of the nodes. Moreover, the hardware is design to switch into active and sleep mode. The application for which it is going to be used and the protocol which is going to be implemented, they both need to consider this point during the integration.

WSNs use Tiny OS as the operating system. Tiny OS is the event driven programming model instead of multithreading operation. On same platform other OS like LiteOS, Contiki and 6LoWPAN had be newly developed for WSNs. These OS designed in such a way that it enables the sensor node as and when an event occurs. During other time, sensor node remains in sleep mode to save the energy. Every sensor integrated with small 8 bit microcontroller or 64 bit microprocessor. They have limited data storage capability; typically the size of RAM is of few kilobytes. When WSNs node put open in front of the world, it is very much difficult for the WSNs node to cop up with multiple events and user at a time with its bounded resources.

2.6 Security

WSNs node is not fundamentally secure [12]. They are deployed in the event prone area: either into the event or near to the event. It uses wireless channel for data transmission. Any malicious adversary can wield the node as per their malevolence intensity. Here we talked about the particular region of the WSNs but when we talked about the integration of the WSNs with the IoT, we open the access of the node to the world. IoT is very much vulnerable for the external attack [13–15]. Integration implies that now the WSNs node is also suffers from the same vulnerability as shown in **Figure 9**. The attacker would able to threaten the WSNs from anywhere in the world. Any malware from the internet can create an adverse effect on the functionality of the WSNs.

- Malicious Node Attack: In this type of attack, an attacker can create a malicious node among two nodes or more than two nodes as shown in **Figure 10**. Node A is sending some data to node B via node C. An Adversary first inserts the replica of node C into the network. This malicious node will alter the communication path between a sender and a receiver. Now the malicious node C can access all the data and can modify it for its malicious intense. The attacker can use multiple malicious nodes for this attack [16].

- Sink Hole Attack: In a sink hole attack, an attacker first compromise one node in the sensor network and through that it propagate fake information about the routing information. By sending the fake routing information it attracts traffic from the network. Once it has access the data it can alter it or can drop some data. Moreover, it also increases the energy consumption in network

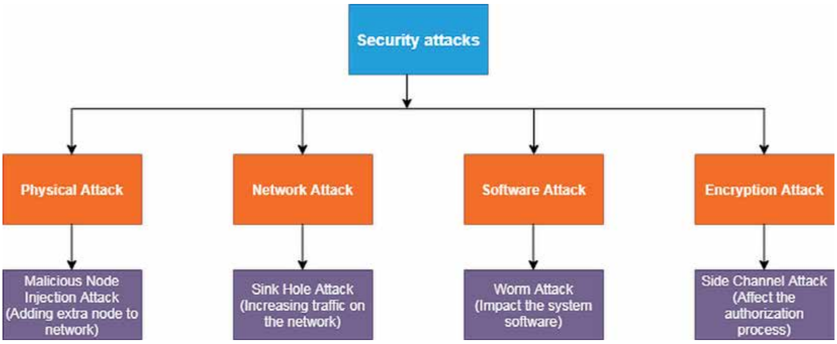

Figure 9.
Security attack on WSNs.

by unnecessary communication. That is indeed a critical situation for energy scary network like WSNs (**Figure 11**).

- Warm Attack: In a warm attack, an adversary can degrade the system operation by corrupting the system software. It is implied by the malicious code in the node. Once the node becomes the victim of a warm attack it can be denying its service to the neighbor, modifying the information, or may get access to important information. Warm is capable to reproduce itself.

- Side Channel Attack: This kind of attack wreck the encryption mechanism and get the private key. The attacker breaches the side channel information. Side channel information contains timing information, power consumption or electromagnetic leaks. Catch attack, timing attack, power monitoring attack, acoustic crypto analysis are some of the example of side channel attack.

One solution to that is WSNs must be protected by the powerful gateway. This solution is not feasible in the current infrastructure as it comes with scarce resources in the WSNs [17–20]. It is sheer essential to provide fundamental security measures to the sensor node while connecting to the internet [21]. We can use encryption techniques like symmetric key encryption model or public key encryption model for the communication. To implement the encryption model, it requires a secure key infrastructure that can provide a secure key for communication. It seems fascinating but it is a strenuous task to implement the encryption model in WSNs which comes with a large number of nodes. Moreover, it adds extra overhead to the communication which is an undesirable condition, especially with scarce

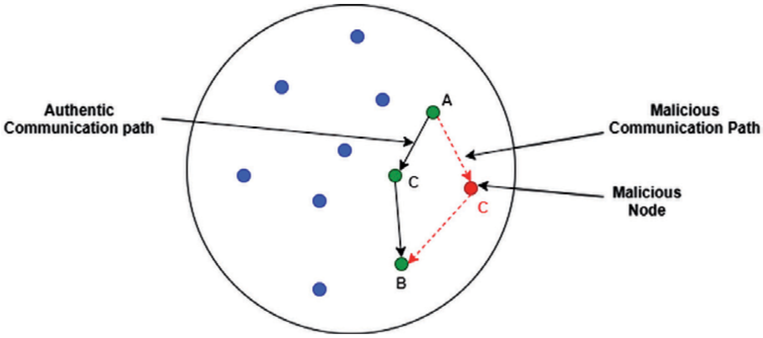

Figure 10.
Malicious node injection.

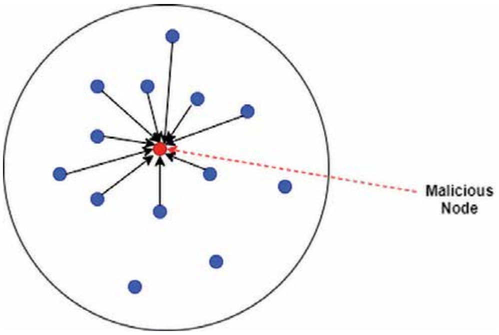

Figure 11.
Sink hole attack.

resources. It is also required deliberate dealing with the switching of sensor node between sleep mode and active mode [22].

When a sensor node connects with any internet host (human or machine) the first task is to provide authentication to the user. Internet user must need to prove his identity that he/she is the right person who collects the data whereas node must need to assure that it offers it services to the right client. There are certain scenarios where the level of authorization varies with the user, i.e. a public space like a library where any user can access the data on the other side, in a private organization or in a defense organization only a limited person can access the data [23].

Another important aspect is to keep a record of communication to enhance security. The internet is full of the heterogeneous user. When we integrate WSNs with the internet, we are opening the doors of WSNs to heterogeneous users. They can access data as well as modifying the data. The internet has an abundant amount of resources. They can store the communication detail in a large server, but on the other side sensor node comes with limited resources. It is very much difficult for the sensor node to keep track of all the communication. Consequently, it is mandatory to find a mechanism to store that data either at the node or in a special server [5, 24].

3. Conclusion

Integration of IoT and WSNs enables the broad opportunity in almost every aspect of the life. The integration seems fascination at first look but it comes with unseen challenges. In WSNs, sensor node is equipped with very low resources in terms of hardware as well as software. Operating system of the sensor node has very low processing capacity and its operation is quite different from the internet node. Hardware of sensor node is designed in such way that it consumes less energy and comes in to active mode as and when any event happens. On the other hand IoT has no limitation either in processing capability or hardware compatibility. In the integration, the layered function of WSNs and IoT has to be tailored for the interoperability. Moreover, WSNs node needs to be updated to deal with the security attacks from the internet. Overall for the faithful integration WSNs has to upgrades it capacity and IoT needs to tailor its layered operation so that it can be compatible with WSNs.

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Wireless sensor networks (WSNs) consist of tiny sensors capable of sensing, computing, and communicating. Due to advances in semiconductors, networking, and material science technologies, it is now possible to deploy large-scale WSNs. The advancement in these technologies has not only decreased the deployment and maintenance costs of networks but has also increased the life of networks and made them more rugged. As WSNs become more reliable with lower maintenance costs, they are being deployed and used across various sectors for multiple applications. This book discusses the applications, challenges, and design and deployment techniques of WSNs.

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