RELIABLE AND ENERGY EFFICIENT MECHANISMS FOR WIRELESS SENSOR NETWORKS

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Abstract

Sensor nodes and their underlying communication technologies are characterised by restricted power resources, restricted processing, limited storage capacities, low data rates and lossy links, and they may also comprise up to a thousand nodes. Wireless Sensor Networks (WSNs) require effective methods for data aggregation, forwarding and processing in order to preserve the limited nodes resource.

Energy efficiency in WSNs has been widely investigated; it is still a challenging dilemma, and new mechanisms are required to fulfil the identified gaps in the literature. In most of WSNs applications, the energy cost has a significant effect on the network lifetime. Along with the energy efficiency, the Network Scalability and Data Reliability are other challenges affecting the performance of robust sensor network. Consequently, network reliability increases at the expense of energy consumption due to the traffic generated to maintain forwarding paths. On the other hand, scalability is a key component of WSNs because, for example, the network may need to grow to cover more space. Therefore, adding more nodes to the network will increase the number of data traffic within the network. Thus, these challenges impose the need to develop new mechanisms that cope with this sensor network requirements and be able to scale while providing efficient data routing and less energy consumption.

Clustering mechanisms are among the most commonly recommended approaches by the research community to sustaining a sensor network throughout its lifetime and provide a scalable architecture and reliable data delivery. Despite a number of research activities associated with clustering in WSNs, some aspects of clustering have not yet been adequately investigated. The conflict between energy consumption and reliability results in excessive energy waste; this is mainly caused by a high number of control messages exchanged to select cluster-head nodes and frequent re-clustering process in traditional cluster-based mechanisms. The re-clustering of the entire network in each round, or when one of the clusters depletes their energy, is not effective because of the extensive overhead and re-clustering process used.

The former problems have been solved using three novel mechanisms that enhance the network's Energy-Efficiency, Reliability and Scalability while considering the node's limited resources. The performance of the proposed mechanisms is validated under realistic network settings through extensive simulation experiments under different scenarios. The realistic energy consumption model is considered based on Chipcon CC2420 advanced radio modules implemented in Castalia simulator. The results obtained revealed that proposed mechanisms outperform the existing mechanisms in term of energy consumption while achieving reliability and scalability.

THESIS CONTENTS

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List of Abbreviations

AC	Alternating Current
ACE	An Emergent Algorithm for Highly Uniform Cluster Formation
ACQUIRE	Active Query Forwarded in Sensor Networks
ADC	Analogue and Digital Converters
AP	Access Point
APTEEN	Adaptive Periodic-Teen
BCDCP	Base-Station Controlled Dynamic Clustering Protocol
BS	Base Station
CDMA	Code-Division Multiple Access
CH	Cluster Head
CM	Cluster Member
DD	Directed Diffusion
DLCP	Dynamic Load-Balancing Cluster-Based Protocol
DWCA	Dynamic Weighted Clustering Algorithm
DWEHC	Distributed Weight-Based Energy-Efficient Hierarchical Clustering
EECS	Energy Efficient Clustering Scheme
EEHC	Energy Efficient Hierarchical Clustering
EEMC	Energy-Efficient Multi-Level Clustering
EEUC	Energy Efficient Unequal Clustering
E-LEACH	Energy-Aware Management for Cluster-Based Sensor Networks
FCH	Final Cluster Head
FLOC	A Fast-Local Clustering Service for Wireless Sensor Networks
FND	First Node Dies

GAF	Geographic Adaptive Fidelity
GEAR	Geographic And Energy-Aware Routing
GMR	Geographic Multicast Routing for Wireless Sensor Networks
GPS	Global Positioning System
HCC	Hierarchical Control Clustering
HEED	Hybrid Energy-Efficient Distributed
HGMR	Hierarchical Geographic Multicast Routing
HID	Human Interface Devices
HND	Half Node Die
HT	Hard Threshold
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISTAG	Information Society Technologies Program Advisory
LCP	Load-Balancing Cluster-Based Protocol
LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	Energy Efficient LEACH-C Protocol for WSNs
LEACH-FL	Improving on LEACH Protocol using Fuzzy Logic
LND	Last Node Dies
MAC	Media Access Control
MEMS	Micro-Electro Mechanical Systems
M-LEACH	Multi-Hop LEACH
MOCA	Multi-Hop Overlapping Clustering Algorithm
MWE	Multiple Winners
PANEL	Position-Based Aggregator Node Election Protocol

PEACH	Power-Efficient and Adaptive Clustering Hierarchy
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PRP	Packet Reception Probability
QoS	Quality of Service
REUCS	Two-Level, Unequal Cluster, Lightweight Mechanism
R-HEED	Rotated Hybrid Energy-Efficient and Distributed
RP	Rendezvous Point
RR	Rumor Routing Algorithm for Sensor Networks
RSSI	Received Signal Strength Indicator
RUHEED	Rotated Unequal Heed
SAR	Sequential Assignment Routing
SCH	Sort Cluster Head
SMP	Sensor Management Protocol
SN	Sensor Node
SNA	Social Network Analysis
SNR	Signal to Noise Ratio
SPEED	Stateless Protocol for Real-Time Communication
SPIN	Sensor Protocols for Information Via Negotiation
SQDDP	Sensor Query and Data Dissemination Protocol
SQTL	Sensor Query and Tasking Language
ST	Soft Threshold
STLP	Suggested Transport Layer Protocols
SWE	Single Winner
TBF	Trajectory Based Forwarding
TCCA	Time Controlled Clustering Algorithm

TCH	Threshold Cluster Head
TCP	Transport Control Protocol
TDMA	Time Division Multiple Access
TEEN	Threshold-Sensitive Energy Efficient Sensor Network
TL-LEACH	Two-Levels Hierarchy for LEACH
TQ	Transmission Quality
TTDD	Two-Tier Data Dissemination
UCS	Unequal Clustering Size
UHEED	Unequal Version of HEED
WDCR	Weight Driven Cluster Head Rotation
WPANs	Wireless Personal Area Network
WRCS	Weight and Energy-Efficient Rotating Clustering Protocol
WSNs	Wireless Sensor Networks

List of Publications

1. Alsnousi Essa Ali, Ahmed Yassin Al-Dubai, Imed Romdhani, Mohamed A. Eshaftri, “Reliable and Energy-Efficient Two Levels Unequal Clustering Mechanism for Wireless Sensor Networks.” *IEEE 20th International Conference on High Performance Computing and Communications; IEEE 16th International Conference on Smart City; IEEE 4th International Conference on Data Science and Systems*, pp. 1330-1335, Exeter, United Kingdom, 2018.

2. Alsnousi Essa Ali, Ahmed Yassin Al-Dubai, Imed Romdhani and Mohamed A. Eshaftri, “A New Dynamic Weight-Based Energy-Efficient Algorithm for Sensor Networks.” *Smart Grid Inspired Future Technologies. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering,* vol. 175. Springer, pp 195-203, 2017.

3. Alsnousi Essa Ali, Ahmed Yassin Al-Dubai, Imed Romdhani and Mohamed A. Eshaftri, "A New Weight Based Rotating Clustering Scheme for WSNS." *IEEE International Symposium on Networks, Computers and Communications (ISNCC)*, pp. 1-6, Marrakech, Morocco, 2017.

4. Mohamed A. Eshaftri, Ahmed Y. Al-Dubai, Imed Romdhani, and Alsnousi Essa. “Weight Driven Cluster Head Rotation for Wireless Sensor Networks.” *The 14th International Conference on Advances in Mobile Computing and Multi Media (MoMM*, 327-331, Singapore, Singapore, 2016.

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Declaration

I, Alsnousi O E Ali, confirm that this thesis submitted for assessment is my own work and is expressed in my own words. Any uses made within it of the words of other authors in any form, e.g., ideas, equations, figures, text, tables, programs, etc. are properly acknowledged. A list of references employed is included.

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Chapter 1

Introduction

1.1 Overview

"*The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it*" 1991, Mark Weiser

THis was Mark Weiser's vision for the 21st century. He coined what is now called ubiquitous computing or pervasive computing [1], which is the process by which everyday objects become smarter by integrating computing devices and interacting seamlessly with humans in the background while serving them in their tasks of daily life. Almost ten years later, the European Union's Information Society Technologies Program Advisory (ISTAG) reinforced Weiser's vision in a statement released in 1999. The ISTAG statement coined a new term "*ambient intelligent*", which is a novel vision of how an intelligent environment will surround people. The evolution of ubiquitous computing and ambient intelligence, as well as the advancement of Micro-Electro-Mechanical Systems (MEMS) and low-power devices, led to the development of a wide range of applications. These different technologies encompass Wireless Sensors Networks (WSNs).

WSNs are a vital technology for modern economic and academic research. The constant miniaturisation of sensor nodes has made it possible to proliferate new

Internet of Things (IoT) applications [2]. Rapid evolutionary shifts in technologies occurred, leading to the creation of new applications. WSNs become an essential feature of this evolution. Sensor nodes are characterised by several resource constraints such as a limited power source (batteries), processor capabilities, data storage and limited transmission range [3]. Among these aspects, the sensor node's energy has been the research community focal point in WSNs. On the other hand, significant emphasis has been placed on research aiming to address the scarce resources of sensor nodes [4]. Typically, WSNs consist of numerous, tiny, self-organised sensor nodes connected by wireless links, deployed either densely or sparsely to observe a physical phenomenon and report obtained data to the Base Station (BS). By means of a wide range of applications, WSNs are becoming an essential part of our lives. In some WSNs applications, the nodes are unreachable when deployed; thus, it is impossible to replace or recharge their batteries [4].

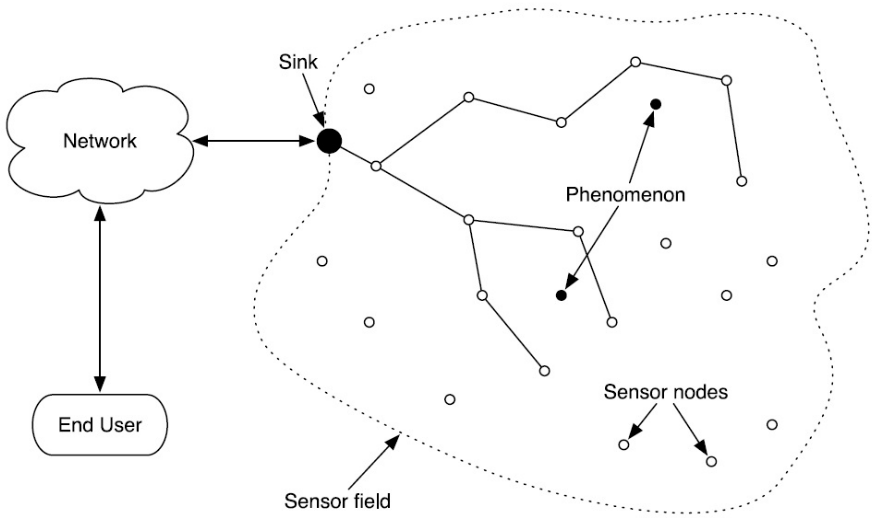

Figure 1: Typical Wireless Sensor Network Structure

The sensor node is composed of a sensing unit, a data processing unit, memory, power supply, and radio and actuator [3]. Since the sensor nodes have limited memory and are usually deployed in difficult and harsh areas, radio is enabled for wireless communication to transfer the data to its neighbour node for forwarding to, or directly communicating with, the base station [4]. The battery is the main power source for sensor nodes [5]. Sensor nodes can sense, measure and gather information from the environment. They also can transmit collected data to the end-user to take the proper action. Sensor networks have no infrastructure [6]; they have composed of tens to thousands of sensor nodes operating together to conduct specific tasks.

One of the features that make WSNs unique in comparison to other networks is that their cooperative effort to accomplish tasks collectively. These features can ensure the use of sensor networks in a wide range of applications such as within military, health care, environmental monitoring and home contexts [7].

WSNs can be distinguished from other types of wire/wireless networks in terms of the communication and deployment of nodes in a physical area [8]. One of the main differences between WSNs and other networks is the nature of networking. In WSNs, the network interacts with the environment more than with humans; sensor nodes are usually placed in the area of interest to sense some phenomenon, whereas other networks operate close to humans since most nodes in these kinds of networks contain devices that are designed to be used by a human being; for example, PCs and mobiles. Nodes in sensor network density are deployed more than other networks such as ad hoc networks [9].

1.2 Motivation and Scope

We are currently experiencing the third wireless revolution (Internet of Things). The first wireless revolution emerged in the 1980s with wireless cellular networks, developing into the wireless data networks revolution in 1999. WSNs are expected to be a viable technology for a variety of IoT applications. Due to the proliferation of new IoT applications [10] and the production of inexpensive costs, sensor nodes might allow for dense deployments in some applications. The dense deployment of hundreds, or even thousands, of sensor nodes, offers a wide range of possible new applications. Current and future application areas include, but are not limited to, habitat and environment monitoring, disaster control and operation, military and intelligence applications, object tracking, video surveillance, traffic control, industrial surveillance and automation, as well as healthcare and home automation [10].

In the future, environment sensing will become a more and more ubiquitous and habitual feature of humans' daily lives. Sensor nodes (SNs) can be defined as multifunctional miniature nodes of low cost, heavy energy consumption and limited processing capability. This creates a requirement for research that applies and develops strict algorithms considering SNs' limited resources. Thus, it's required that sensor module device hardware and software, must be developed and designed to cope with high energy consumption and serve the application as long as possible [11], [12]. The main objective of WSNs is data-gathering from the physical world and performing limited processing before relaying it to the BS using wireless communication to undergo further analysis and take necessary actions. In some critical applications, the data transported from nodes to BS could be crucial, and data loss cannot be tolerated [13]. Generally, sensor nodes are distributed autonomously over an area of interest in tens, hundreds and even thousands, depending on the application. In terms of critical applications, where the SNs can be deployed in harsh environments or areas that are inaccessible to human, it would be impractical to replace faulty nodes or change their battery because of the node's short battery life [6]. Thus, it highlights many challenges; research is required for preserving the node's energy and achieving a more reliable network.

To prolong the overall operational lifetime of the network, the energy consumed by nodes should be minimised as far as possible. Most of the node's components will, therefore, be turned off most of the time and will only be used if they are required [14]. For example, the processing unit can be put into a low-power sleep mode while it is idle. Turning off the wireless communication radio also conserves a significant amount of energy, since transmitting one bit consumes as much energy as about 1,000 processing instructions [15]. Thus, communication in WSNs is one of the primary sources of energy consumption and deserves particular consideration.

1.4 Aims and Objectives

This research aims to investigate and develop new, energy-aware algorithms to increase the lifetime of WSNs' by considering node constraints resources and routeing data. The primary concern of this research is sensor networks, which consist of large numbers of nodes that can be scalable.

Mostly, in existing cluster-based WSNs, the Custer-Head (CH) is rotated within the cluster in each round [16][17][18][19], which increases the network lifetime and distributes the energy consumptions throughout the network. When some nodes become a CH, these nodes consumed more energy than other nodes in the network, due to handling clusters inter/intra traffic [20]. The traditional rotation technique/process more quickly consumes the energy of all the sensors to such an extent that, after a point, if any sensor becomes a CH, its energy may exhaust, and it may not be able to continue to the end of the round [21]. The information gathered by that CH is also lost in the process. If the steady-state phase is shortened to reduce the loss, it will increase the overhead of the setup phase and, still, there will be losses due to the death of the CHs [22].

These data losses can be vital [23]. The data transfer reliability in WSNs is of enormous importance for critical applications where the loss of single pieces of information about any event is crucial [23]. Suggested Transport Layer Protocols (STLP) [23] provides end-to-end reliability or reliable transfer of the data from a source to a destination, but they do not cater for data loss due to the failure of the CHs. The CH failure scenario arises when no sensor node in the network is capable of running the entire round alone [24]. So, a sensor, even with the highest residual energy, will be susceptible to failure before the round's completion. The main objective of this research is to reduce the loss of data due to CH failure during a round, provide continued coverage to that cluster until the new round starts with a new CH, all while keeping the node's energy in mind. The aims of this research, and hence this thesis, are:

- **Energy-Efficient algorithm:** design new energy-aware algorithms, considering the node's limited resources and the network as a whole.
- **Scalability of the network:** develop a scalable algorithm while maintaining the operating efficiency of the network when the number of nodes is dramatically increased.

- **Reliable routing algorithm:** model a reliable and robust network, while keeping in mind the limited resources and critical applications of the sensor nodes.
- **Modelling and simulation:** evaluate the new algorithms using a suitable simulator.

1.5 Research Contributions

This research has contributed to the existing WSN's research efforts in term of energy efficiency, data reliability and scalable network architecture. Most of WSNs applications required an efficient recourse usage due to the inherent characteristic of sensor nodes. A typical scenario of sensor nodes applications is the random deployment of a large number of sensor nodes over the area of interest. The deployed sensor nodes sense and communicate with neighbouring nodes and perform necessary computations of collected data locally before its being sent to the base station. This process poses further challenges to the Energy-Efficiency, Reliability and Scalability for any new mechanisms to be applied. Thus, three novel mechanisms have been proposed to enhance the network's Energy-Efficiency, Reliability and Scalability, while considering the node's limited resources. The following section highlights the three contributions.

(1) **First contribution:** "*A New Dynamic Weight-based Energy-Efficient Algorithm for Sensor Networks (DWCA)*", The proposed mechanism aims to fulfil the gap in existing mechanisms, where the cluster-head nodes are selected by probabilistic approaches or periodic reassignment within randomly deployed nodes. This strategy helps to prevent the problem of a node failure in the event of energy depletion or external damage. However, using such an

approach can result in selecting nodes with less energy or that have been selected before for the CH role. The proposed mechanism has overcome these issues by considering more than one factor in deciding which nodes become the cluster-head in each round. The cluster- head nodes are selected mainly by taking into account the node's residual energy, location within deployment filed, and the distance from the BS. By combining these factors, the new mechanism ensures, the dynamic selection process of Cluster-heads nodes where no BS or end-user will be involved in the clusters constructing process. This is critical requirements for many applications when the nodes are randomly deployed. The new mechanism introduced a new type of *CH candidate* selection to ensure the nodes that become CH are distributed throughout the sensing field. This mechanism has proved that it reduces overall energy consumption among all the nodes and improves scalability compared with counterpart mechanisms.

(2) **Second contribution:** "*A New Weight based Rotating Clustering Scheme for WSNs (WRCS)"*, The proposed mechanism aims to tackle the issues of excessive energy consumption and data loss while routing the data within the network or to the base station as well as the flexibility in accommodating any number of nodes. Data loss is a vital issue in WSNs application where reliability is a huge importance for critical applications where the loss of single pieces of information can have a critical impact on the application. The new mechanism enhanced the network lifetime by the new strategy used to elect the most suitable nodes to become CHs, where the selection is based on node's weight. The weight of each node is determined using a combination of metrics, including the average number of neighbours, remaining energy and

transmission quality. The combination of these metrics for each node is to select the best cluster-head node. The data loss is reduced in the proposed mechanism by utilising multi-hop data routing among the clusters as well as rotating method inside the cluster has reduced the energy consumption.

(3) **Third contribution:** "*Reliable and Energy-efficient, Two-levelled Unequal Clustering Mechanism for Wireless Sensor Networks (REUCS)"*: This study relates to load-balancing and the reliability of the network in terms of the intra/inter-cluster communication patterns by using two levels of unequal clusters. Moreover, to fulfil the gap in well-known unequal clusters mechanism, where the small cluster near the base station depletes their energy faster than the one far away. The vital objective of clustering is to maximise network lifetime, stabilising network topology, data aggregation and scalability. The conflict between the energy consumption and frequent re-clustering of the entire network results in excessive energy waste; this is mainly caused by control messages exchanged to re-cluster the network in each round. The re-clustering of the entire network in each round, or when one of the clusters depletes their energy, is not practical because of the extensive overhead and re-clustering process. The newly proposed mechanism proposed Two-Levels clusters technique, the cluster in level one that is near the base station is smaller than the one far away. The purpose of this new technique is to resolve the hotspot issue of nearby BS cluster, where they deplete their energy faster than the one far away, due to the incoming traffic load. The loss of these critical CHs will significantly affect the performance of the network and could isolate the BS from the nodes. Consequently, new levels of architecture and local CH rotation have been developed. The new proposed re-

clustering scheme within network levels aims to stabilise network topology and conserve network energy. Unlike the clustering mechanisms in the literature, the new mechanism elements the frequent re-clustering for the entire network.

1.6 Thesis Outline

- Figure 1 represents the chapters and sections concerning the core aims of this thesis.

	Energy – efficiency	Cluster-based routing	Modelling and results
CHAPTER 2 – Wireless sensor network technologies	Sections 2.1, 2.2 and 2.3	Section 2.7	
CHAPTER 3 – Clustering in WSNS	Sections 3.3	All the section	
CHAPTER 4 – A new, dynamic, weight-based energy efficient algorithm for sensor networks	Sections 4.2	Sections 4.3	Sections 4.5 and 4.6
CHAPTER 5 – A new, weight-based Rotating clustering scheme for WSNS	Sections 5.1 and 5.2	Sections 5.3	Sections 5.4
CHAPTER 6 – Reliable and energy-efficient A two-levels Unequal clustering mechanism for WSNs	Sections 6.1 and 6.2	Sections 6.3	Sections 6.4

Figure 2: Thesis Sections and the focus on Research Aims

- **CHAPTER TWO – WIRELESS SENSOR NETWORK TECHNOLOGIES**

Presents a general overview of WSNs, including, sensor nodes structure, current applications of WSNs and some evaluation metrics for sensor network outlined as well as a short description of the protocol stack, network architecture and routing technologies used in WSNs.

- **CHAPTER THREE – CLUSTERING IN WSNs**

In this chapter detailed description of clustering approaches in WSNs is presented, providing an overview of cluster-based techniques, which include, the properties of clustering, methods and the objective of clustering. Most importantly, in this chapter, an analytical review of the prominent cluster-based approaches presented, including the advantages and disadvantage of each method.

- **CHAPTER FOUR – A NEW, DYNAMIC, WEIGHT-BASED ENERGY EFFICIENT ALGORITHM FOR SENSOR NETWORKS**

Chapter four presents the first problem that motivated this research, providing all the design description beside explanation for the proposed architecture components and evaluation for the experiments.

- **CHAPTER FIVE – A NEW, WEIGHT-BASED ROTATING CLUSTERING SCHEME FOR WSNs**

Chapter five provides the second major contributions of this research, which introduces a new technique for clustering the sensor networks. The second contribution addresses some drawback of the first contribution and provides a more robust, scalable and energy-efficient sensor network, which is the proposal of an improved version of the previous protocol.

- **CHAPTER SIX – RELIABLE AND ENERGY-EFFICIENT, A TWO-LEVELS UNEQUAL CLUSTERING MECHANISM FOR WSNS**

Chapter six presents this third research contribution, which is the major work of this research that concludes the deep insight into sensor network issues. This contribution addresses the issues of unequal clustering in WSNs. In chapter six, the more detailed description provides with simulation results that prove the validity of this contribution.

- **CHAPTER SEVEN – CONCLUSION AND FUTURE WORKS**

This chapter concludes the research contributions by summarising its findings and outlining possible future research directions for clustering in WSN.

Chapter 2

Wireless Sensor Networks Technology

This chapter presents a general overview of WSNs technology, including, sensor nodes structure, current applications of WSNs and critical evaluation metrics for sensor networks outlined as well as a short description of a protocol stack, network architecture and routing technologies used in WSNs.

2.1 Sensor Node

An SN is a tiny and smart device, which's constrained in terms of energy source, node size and processor capabilities [3]. SN can be scattered in an area of interest and form sensor networks autonomously by communicating through wireless links. These devices have the ability to collaborate to collect and transform the physical world data to the end-user for further analyses. Accordingly, sensors require effective methods for data aggregation, forwarding and processing. This section covers the fundamental elements of a sensor node's hardware, which composed of four main subsystems, sensing, processing, transceiver and a power supply unit [3] [6] [13]. Figure 3: depicts the sensor nodes components.

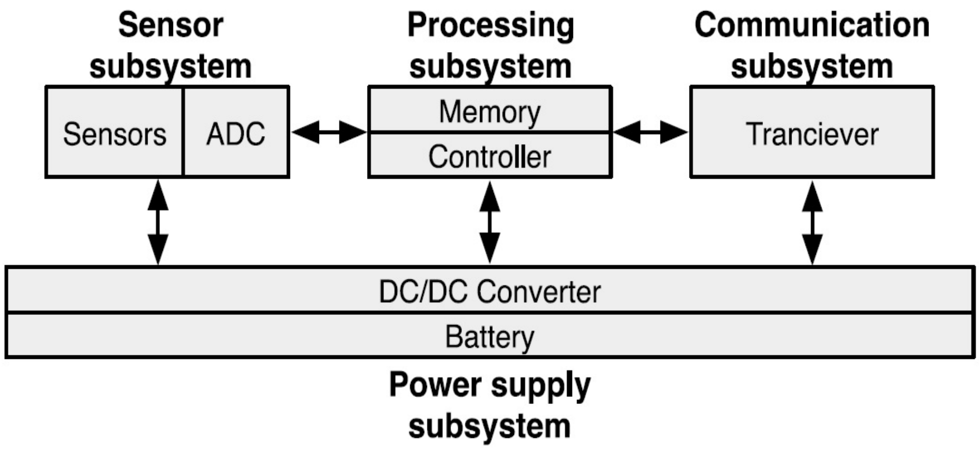

Figure 3 Sensor Node Components

2.1.1 Node Sensing Subsystem

This Subsystem comprises a sensing unit, which is used to detect the event in a specified area and performs an Analogue to Digital Conversion (ADC). One sensor node can have several sensing units, for things such as light, humidity, pressure and temperature, among others [25].

2.1.2 Node Processing Subsystem

This unit includes the processing and controller unit in SN is responsible for managing the procedures and tasks assigned to the node in order to collaborate with its neighbouring nodes in the network [25].

2.1.3 Node Communication Subsystem

This unit includes a transceiver unit which enables transmitting and receiving functions for the sensor node and achieves the connectivity within the network [25].

2.1.4 Node Power Supply Subsystem

In most of the application considered in this research, the SN will be equipped with limited power battery as the only energy source. In recent year, the research community have been investigating new technologies to be used as energy sources for the SN, such as energy harvesting (solar power) [25] [26].

2.2 Prominent WSNs Applications

WSNs can be constructed by different sensors, depending on the application. Infrared sensors, Visual sensor, Acoustic sensor and Thermal sensor are used to acquire physical information [27]. Such sensors can observe a varied range of environmental conditions, such as light, temperature, soil and noise levels. These broad-ranging applications are possible in sensor networks. The following sections describe the main WSNs applications [28]. Figure 4 represents some of WSNs application

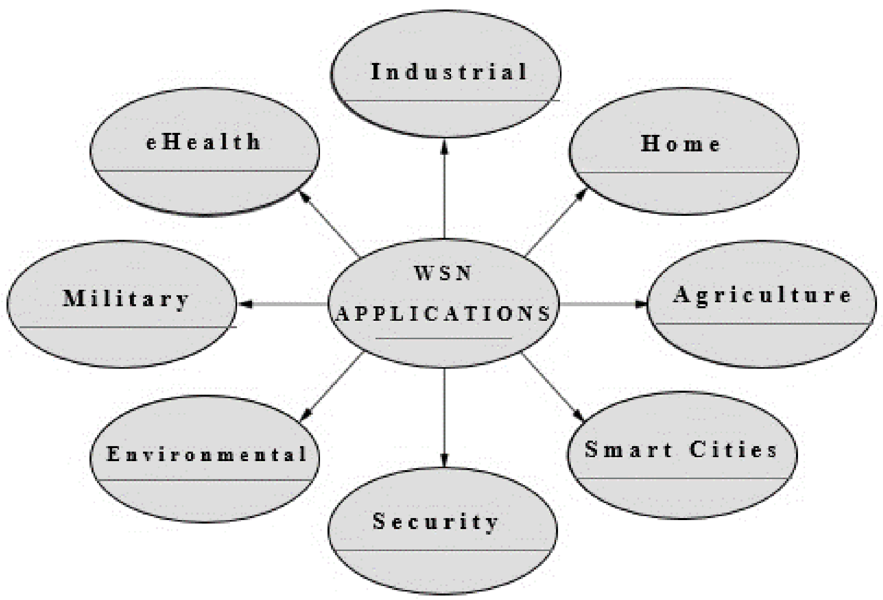

Figure 4: Wireless Sensor Network Applications

2.2.1 Environmental

The utilisation of WSNs in environmental applications has gained a wide range of interest in many areas, including forest fire detection, flood detection and pollution. Moreover, tracing animals and insects movement, livestock and irrigation, more environmental applications are given in [7].

2.2.2 Military

WSNs have been in use in various military applications, in [29] several examples demonstrated such as intelligence, surveillance, reconnaissance, communications, military situation awareness, as well as the detection of mass destruction and enemy movement. The capabilities of sensor networks and the speed at which a network can be configured when utilising small and tiny devices is what makes it promising, reliable technologies for military operations.

- Smart Dust Project

It’s one of the well-known military applications uses sensor nodes in battlefield surveillance monitoring [30]. Smart Dust aims to provide military forces with technologies needed for carrying out operations in environments that can be unsafe for individuals to access. The unique characteristics of sensor networks as both self-configuring and self-organising, means they are capable of assessing the need to obtain information from hostile areas.

- Sniper Detection system

The PinPtr system application [13] was developed to locate and detect snipers. The application uses acoustic sensors to sense the shock waves generated by the gun-fire, mostly it used for counter-sniper. When a sensor detects the event, it can estimate the position of the shooter.

- VigilNet

The VigilNet application uses the smart motion sensor in order to detect any movement within deployed sensors. The data in VigilNet routed to the end-user in a multi-hop manner, which makes it energy-efficient application [30]. The network topology constructed in Cluster-based structure to provide more manageable network resources.

2.2.4 eHealth

A particularly important utilisation of smart sensors is in the monitoring of patient health [31]. WSNs applications are crucial to the healthcare sector and are now at the core hospitals and clinics. The sensors can monitor the conditions of the patients both in and out of a hospital and have additional applications in diagnostics and drug administration.

2.2.3 Industrial

The industrial sectors benefited from the use of sensor network in many different applications [8] The unique features and flexibility in deploying a large number of sensor nodes as well as the low cost associated with this devices, have made this network as a great option for current and future industrial. Examples for current applications including, monitoring of manufacturing process/flow and security systems for the buildings.

2.2.5 Home

As technology advances and more new applications emerging, the SN will play a key role in these applications. Some of the current home applications, including smart appliances [32] and monitoring home utilities [33].

2.3 WSNs Evaluation Metrics

In Figure 5, the most relevant evaluation metrics for this research are demonstrated, which examined in briefly in the following section

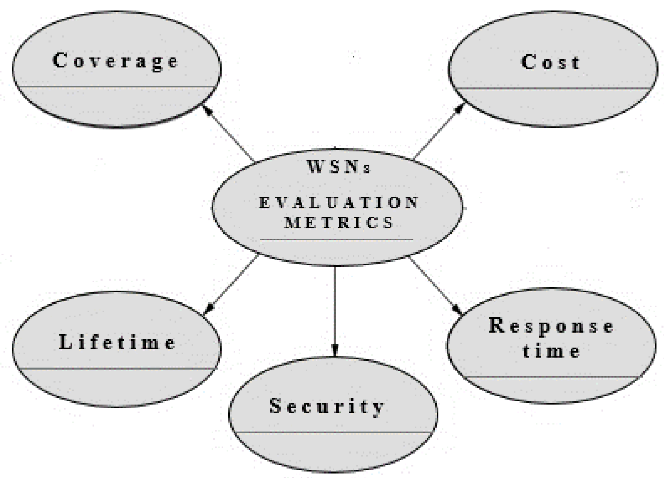

Figure 5: WSNs Evaluation Metrics

2.3.1 Lifetime

When deploying a group of nodes to form a network in a specific area that could be difficult to access, lifetime is the most critical element of wireless sensor networks. The main energy source is the battery attached to the nodes. Furthermore, this network can be in use for several month or years; in this case, the lifetime of this network has to be managed to prolong its existence. To maximise SN and entire network lifetime, its essentials to consider nodes hardware and software before setting the application. [34], [35] states that it is possible to harvest energy from external sources to keep the network operating. However, in some application scenarios, the nodes require to be completely power-dependent [26]. In this case, the nodes must contain enough energy to last for the intended time-period, or they will be required to scavenge energy from the environment through devices; for example, solar cells or piezoelectric generators [5]. When using these two methods, the average energy consumption of the nodes has to be kept as low as possible.

2.3.2 Coverage

It's one of WSNs primary evaluation metrics to ensure the connectivity of the network [5]. One of the advantages of the WSNs is the flexibility of deploying the nodes over a large physical area; having all nodes in the range of the coverage can significantly increase a system's value and performance. Scalability [13] is a key component of WSNs because, for example, the network may need to grow to cover more space. Therefore, applied algorithms must cope with this requirement and be able to scale while providing efficient data routing.

2.3.3 Cost

What makes WSNs unique from other networks is their ease of deployment. For system deployment to be successful, the WSNs must configure itself autonomously [25]; it must be possible for an untrained person to place nodes throughout the environment and for the system to work efficiently. Hence, one of the wireless sensor network's functions is to configure itself for any possible physical node placements automatically; it is not possible to have nodes with infinite range [26]. The WSNs must be capable of providing feedback for any constraints and any potential problems that can affect network quality [9]. Besides, the system must be able to adapt to any change of environment or condition.

2.3.4 Response time

The response time metric is a critical performance metric [14]. The nodes in the network must be able to respond immediately to any event that occurs around the nodes, at any time, without notes. In general, utilising sensor nodes for monitoring offers a great benefit to many application process controls [36].

2.3.5 Security

Keeping information collected from the sensor nodes secure is extremely important, even if environmental information, such as temperature or light, is harmless. The WSN must, not only ensure the privacy of the data but also be capable of authenticating data communication. Deployed SN should not tolerate any false messages or send a duplicate received a message by the end-user (BS) [37][38].

2.4 WSNs Protocol Stacks Layers

An extensive effort of publication has been contributed, aiming to achieve energy-efficiency in the area of sensor networks. These efforts focused on both sensor node hardware and software. Concerning software, many protocols have been developed, and others have been adopted from other types of networks, such as ad-hoc networks [39]. All such protocols aim to increase energy efficiency and the reliability for WSNs applications. In figure 6, the Protocol Stack Layer for a sensor network is shown, and in addition, the following section explores more details.

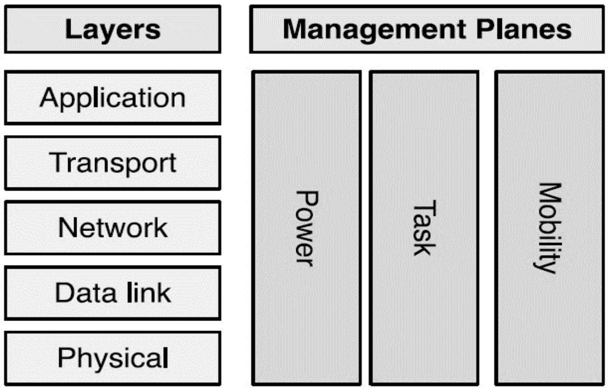

Figure 6: Wireless Sensor Networks Protocol Layers Stacks

2.4.1 Application

The application layer consists of several management functionalities that perform various sensor network applications, such as node localisation, query processing, time synchronisation and provide security management for the network. Sensor Management Protocol (SMP), is one of the application-layer protocols which responsible for handling nodes software procedures in order to accomplish specific tasks for the sensor network application. Another example for application layer protocols is Sensor Query and Data Dissemination Protocol (SQDDP) which facilitate the access to running application by providing an interface accessible to the end-user or network administrator. Finally, the Sensor Query and Tasking Language (SQTL) constitutes a protocol used on the application layer to provide a programming language for the sensor nodes.

2.4.2 Transport

In traditional networks, the Transport Control Protocol (TCP) is used when connected to the internet or external networks. Due to the resource constraints of SN, particularly with limitations of storage, computation and energy – applying the TCP protocol on sensor nodes is not efficient [18]. These limitations prevent the direct use of traditional TCP without some modifications. Sensor Networks have been applied in many contexts, including the military, healthcare and the environmental sectors. The variety of sensor applications poses more reliability requirements when deployed, and thus, the development of TCP for sensor networks is not possible up to the date due to the limited node's resources. According to [18], utilising the TCP protocol in SN requires new schemes to manage the communication among the nodes.

2.4.3 Network

The main responsibility of the network layer is managing routing tasks of the sensor nodes within the network. When sensor nodes are deployed in a specific area of interest, the data needs to be transmitted to the BS. It can be transmitted directly via a single-hop or multi-hop manner. The single-hop manner is costly for sensor nodes in term of both energy consumption and implementation complexity, whereas multi-hop transmission is more effective in term of network energy-efficiency [30].

Since sensor nodes are deployed in a large number of nodes, and they are close to each other, it is possible to use multi-hop, short-range communication in sensor networks to perform short-range communication [30]. A source node must employ a routing protocol to select an energy-efficient, multi-hop path from the node itself to the sink. The network layer of sensor networks is usually designed according to the following principles:

- The importance of power efficiency must be considered.
- Sensor networks are mostly data-centric.
- In addition to routing, relay nodes can aggregate data from multiple neighbours through local processing.

- Due to the large number of nodes in a wireless sensor network, unique IDs for each node may not be provided, and nodes may need to be addressed based on their data or location.

Another important function of the network layer is providing inter-networking with external networks, such as other sensor networks, command and control systems, and the internet.

2.4.4 Data Link

It's primary responsibilities, including multiplexing of the data stream, creating a data frame, error control and medium access [40]. The Data Link layer provides a reliable one to one and one too many connections. The most popular data link protocol is Medium Access Control (MAC), which offers communication management among the sensor nodes [40]. The conventional network's MAC protocols are not suitable for WSNs without modification because the sensor node is resources constrained; particular, the energy source [41].

2.4.5 Physical

The main responsibility for the physical layer is handling data bits received from the data link layer and being converted to smaller bits that are suitable sensor nodes [42]. It is also responsible for selecting the current frequency, data encryption, detection and signal modulation. Moreover, it deals with the design of the underlying hardware and various electrical and mechanical interfaces [42].

2.5 WSNs Standards

Several standards are relevant to wireless sensor networks. This section will explain some of these standards and consider only the communication standards that are specific to low-power Wireless Sensor Networks.

2.5.1 IEEE 802.15 standards family

IEEE 802.15 family defines several standards for WPANs: Most of WSNs use the IEEE 802.15.4 and IEEE 802.15.5 standard [43] [44] [45]. The IEEE 802.15.4 is popular and is now used as the basis for other standards. The IEEE 802.15.4 standard defines and supports two network device: a Full and Reduced Function Device [44].

2.5.2 ZigBee standard

On the top of IEEE 802.15.4 is the ZigBee standard, which defines network and application layers [46]. It is widely used in many applications, including in the home, in building automation, remote controls and healthcare. Furthermore, the Zigbee Standard defines many networks topologies such as star, peer-to-peer, and cluster-tree. A network has one device referred to as a ZigBee Coordinator. This coordinator can be seen as the central node in the star topology, the root in the tree topology, and in the peer-to-peer topology. It can be located anywhere. ZigBee consists of two types: ZigBee and ZigBee pro. Both models support mesh networking and, according to [47] can work with most of the application profiles.

2.5.3 Z-wave standard

The Z-Wave standard has been developed by 120 companies including Zensay, Intel and Cisco. It has many applications, such as building automation and entertainment electronics. Z-Wave consists of a controlling device and AC powered slave nodes.

This slave node can be used as a router, which transmits incoming data from a wireless medium [48] [49].

2.5.4 WirelessHART and ISP 100.11a

WirelessHART and ISP 100.11a are mostly used in industry application processes in which process measurement and control applications have specific requirements for end-to-end communication delay, reliability and security. Both of these standards built on IEEE 802.15.4, a physical layer, and use TDMA [50].

2.5.5 Bluetooth Low Energy

Bluetooth technology has been extended to use in low energy applications [51]. These include Human Interface Devices (HID) and sensor profiles. This technology is different from traditional Bluetooth due to differences in the linking layer protocol as well as in the main functions, for example, variable packet lengths, automatically entering power-save mode when a device is not transmitting, and the exchange data in attribute/value pairs [52].

2.6 Sensor Networks Architecture

The objective of WSNs is to collect data from the ambient environment and send collected data to the Base Station, allowing the end-user to make a proper decision. The objectives of the BS are to monitor the overall network status and receive data from nodes. When a node detects any phenomenon, it transmits those readings to the base station [25].

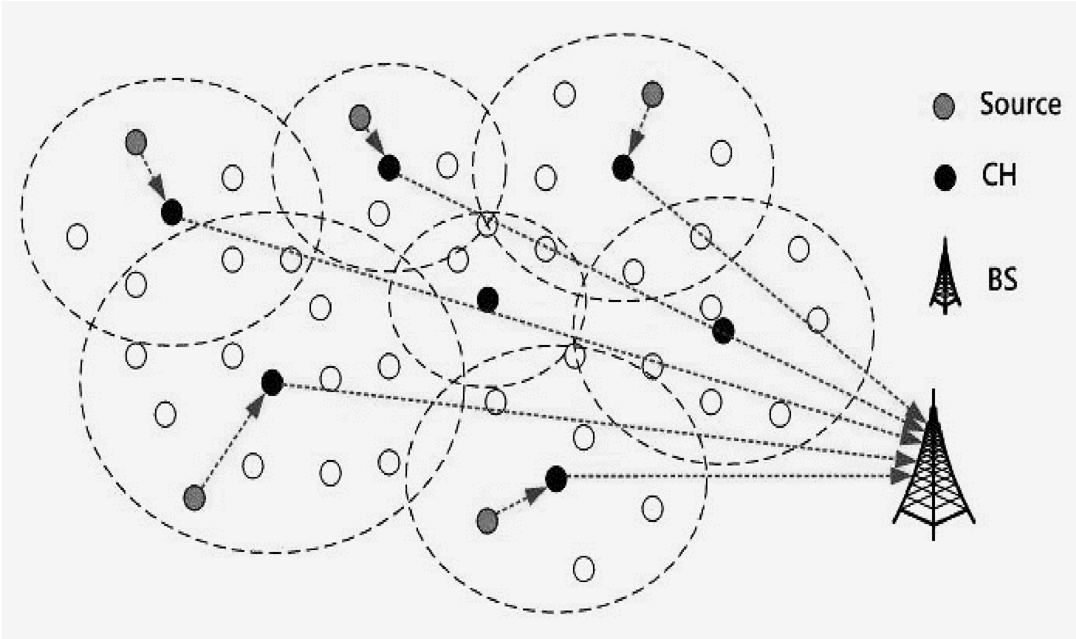

Figure 7: General Sensor Networks Architecture

As shown in figure 8, there are two types of sensor network architectures: single-hop and multi-hop [51]. Single-hop architecture, or long-distance transmission, is when each SN sends its data to the BS directly in one-hop. This mechanism has its disadvantages in terms of energy-efficiency, due to the link cost to deliver the [53]. On the other hand, multi-hop transmission or short-distance communication is when all the SN in a network collaborate to in order to communicate with BS. This mechanism makes the connection between nodes feasible in terms of the network lifetime [53]. The architecture of the multi-hop network can be categorised into two types, as discussed below.

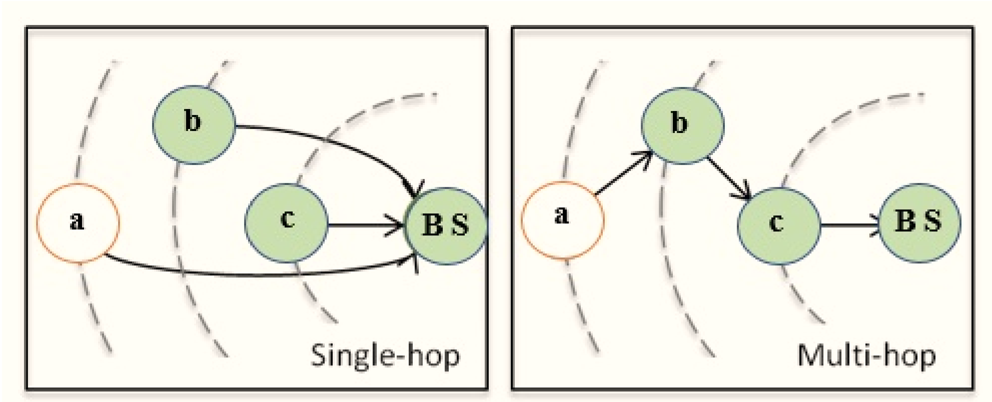

Figure 8: Sing-hop and Multi-hop Routing Structure

2.6.1 Flat architecture

In flat topology, the nodes in the network have the same role in performing sensing tasks. WSNs consist of a large number of nodes; "it is not practical to assign a global identifier to each node to route the data in the network" [54]. One way to tackle this problem is to use data-centric routing [27], where the BS transmits a query to all sensor nodes in a network domain by flooding the domain with this query, asking for specific data and responding only the nodes that match this query. As depicted in figure 9, Each SN communicates with BS through the multi-hop path and relay nodes engage in the process to deliver the data to the sink.

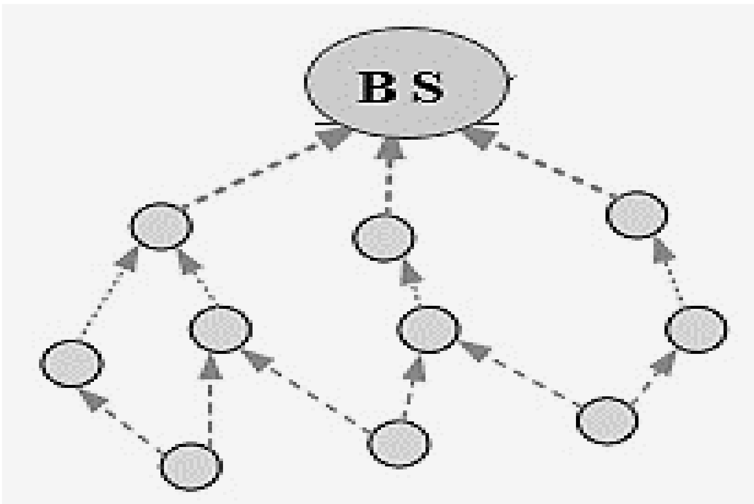

Figure 9: Flat Topology Architecture

2.6.2 Hierarchical architecture

The second category is a hierarchical topology architecture, where sensor nodes are organised into clusters [27][55]. Figure 10 shows an example of WSNs cluster-based topology. The nodes in each cluster have to elect one node to be the head of the network, and any data received or sent from the network has to pass through the CH. The CH needs to be more powerful than other nodes in terms of energy and processing capacity; the rest of the nodes in the network will perform sensing tasks and send collected data to their designated CH, which then forwards this data to the BS [56].

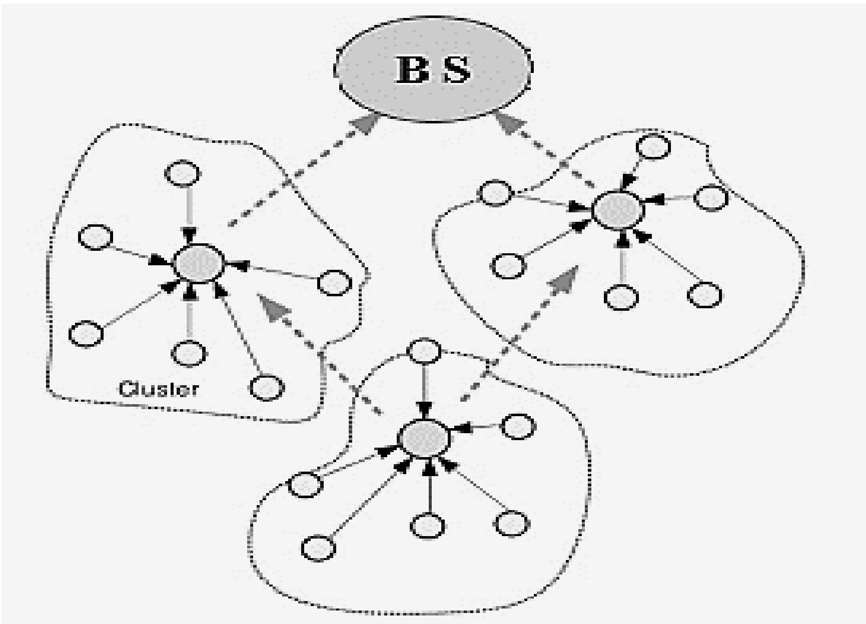

Figure 10: Hierarchical Topology Architecture

This process has many advantages; for example, reducing energy consumption, balancing traffic loads and improving scalability when the size of the network grows [57]. However, this process has some disadvantages. One of the most common problems with clustering arises from how to select the CHs and organise the cluster roles within the network [58].

2.7 WSNs Routing Approaches

The main task of WSNs is to gather and forward data from specific areas of interest towards the BS [55]. Consequently, the algorithms used to handle this task is an important factor for these types of networks. Due to the inherent characteristics of WSNs, routing is very challenging. These routing challenges are mainly due to the difficulty of building a global addressing scheme for a large number of sensor nodes that are deployed in most of the applications since the overhead of ID maintenance is high [25]. Thus, traditional routing protocols may not be suitable for WSNs, because sensor nodes require careful resource management; primarily as the nodes in most WSNs applications operate in an unattended manner [25]. There are several criteria to consider in WSNs routing techniques: the number of nodes deployed; the flow of the data to the BS; the limited resources of the node; that topologies change. In addition, depending on whether the nodes are static or mobile; that applications are specific, and the requirements for each application are different; the positioning awareness of the nodes; and, finally, the requirement to avoid redundancy [4].

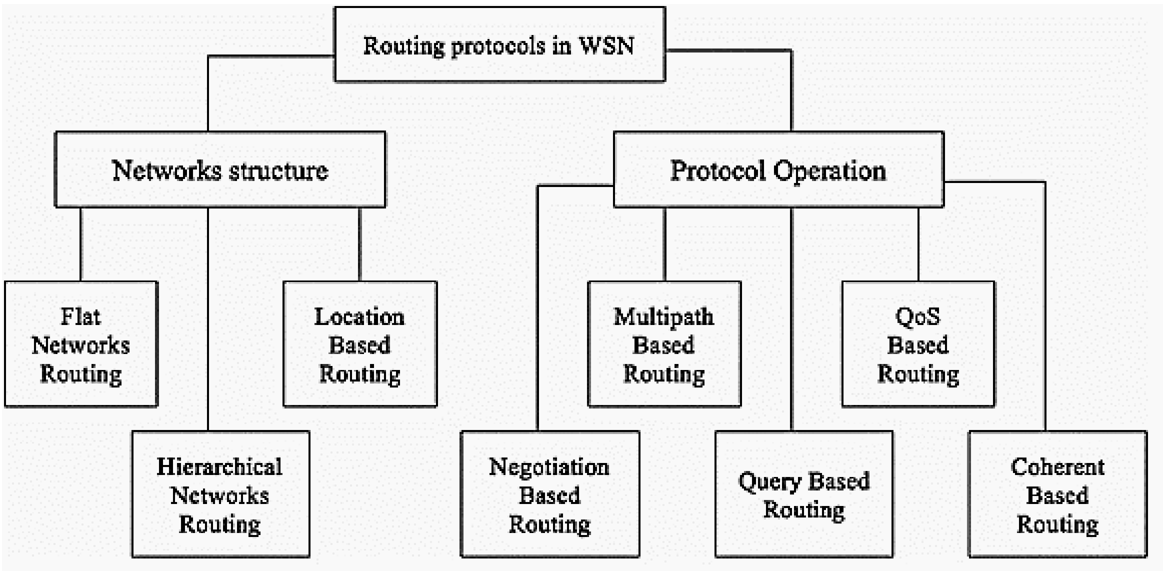

Figure 11: WSNs Routing Protocols Classification

In general, WSNs routing protocols can be divided into two main categories: structure and operation-based protocols. As can be seen in figure 11, Network structure protocols are classified into three groups: flat routing, hierarchical routing and location-based routing protocols. Operation-based routing protocols are divided into five groups: negotiation-based routing, multipath routing, query-based routing, QoS-based routing and coherent-based routing protocols. The following section provides an overview of these routing protocols.

2.7.1 Based on Network Structure

Flat network routing: In this type of routing protocol, all the SN in the network participate equally to route collected data to the BS. Flat-routing is feasible for homogenous nodes and is not required to be location-aware [25]. Because the BS periodically broadcasts the routing path to the nodes in the network. Dynamic location and path broadcasting within small groups of sensors helps to reduce the overhead updates from nodes to BS; Figure 12 shows Flat routing architecture of WSN.

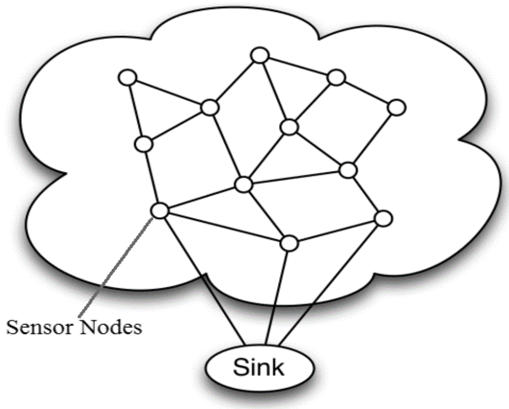

Figure 12: Flat Routing Architecture of WSN

However, flat routing protocols do not scale in large networks (with thousands or tens of thousands) due to the cost of the extremely high number of updates, and network throughput can be affected by broadcasts in each round [59]. Directed Diffusion (DD)

[9] is one of well-known flooding technique, Negotiation-Based Protocols for Disseminating Information (SPIN) [60], and Rumor Routing Algorithm for Sensor Networks (RR) [61].

Hierarchical-based routing: In this type of routing protocol, the network is organised into virtual architecture, such as clusters, grids, strips or rings. These virtual architectures were originally proposed in traditional networks (wire-networks). Dividing the network into sub-groups has many advantages in terms of performing energy-efficient routing protocols for WSNs. The nodes in each subgroup retrieve and store the data, within the created virtual groups, to be forwarded to the sink node by the designated node. As shown in figure 13, Data forwarding depends on protocol design, and it occurs either in one hop to the sink node or along with other subgroups and then to the sink node. A number of hierarchical routing protocols have been proposed for sensor networks, such as [62][63][63].

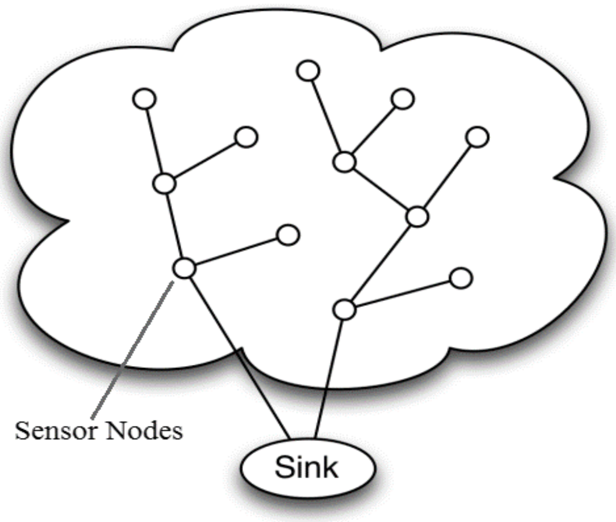

Figure 13: Hierarchical Routing Architecture of WSNs

Location-based routing: In this type, the nodes can be identified by their location, which can be estimated by signal strengths received from neighbouring nodes during the set-up of information exchange. Another way to determine the nodes' location is by equipping the nodes with GPS [13]. The energy-efficiency in location-based schemes can be achieved by dividing the SN field into equal virtual grid zones [64]. The routing cost within the zone will be similar for deployed nodes to some extent. Some nodes in the zone can be turned off to conserve their energy if there is no data to transmit. The most prominent location-based algorithm are: [65] [66].

2.7.2 Based on Protocol Operations

Multipath-based routing protocols: This technique is used to maintain and enhance data flow from source to distinction by creating an alternate path when the primary path fails [67][67]. The energy cost of this technique is always high since both paths are kept alive. Thus, network reliability increases at the expense of energy consumption due to the traffic generated to maintain both paths. An example of this form of routing protocol is Directed Diffusion [68].

Query-based: In this routing protocol, the sink node propagates data queries to nodes throughout the network, and the nodes then check these queries. If it matches the nodes' data, it sends it back to BS. One form of the query-routing protocol is (ACQUIRE) [69].

Negotiation-based routing protocols, in the form of negotiation-based routing, redundant information is eliminated by utilising high-level descriptors by negotiation between SN in the network. The primary advantage of negotiation-based routing protocols is eliminating the duplicated data being forwarded to the BS by employing negotiation strategy between nodes by exchanging a number of messages before sending collected data. An example of the form of protocols is SPIN family [69].

Quality of Service (QoS)-based: In QoS routing protocols, the network must balance energy consumption and data quality when forwarding data to the sink node. The SAR protocol [70] proposed the notion of QoS into routing decisions. The SAR makes decisions based on three metrics: node's energy, the data type and priority level as well as the link quality. (SPEED) Is another model of this type of protocols [71], aims to provide instant end-to-end transmission for SN.

Coherent and non-coherent-based routing protocols, In WSNs, routing protocols employ different data-processing techniques when they are data-flooded in the networks. Data processing in WSNs protocols can be coherent, where the data is sent to an aggregator node for timestamping and the elimination of any redundant data. Whereas, in non-coherent protocols, the nodes process the data locally before forwarding the data to the sink node. The best example of these type of protocols are (SWE) (MWE) [54].

2.8 Summary

In this chapter, an overview of WSNs technologies have been presented. The chapter started with a description of sensor nodes main components including, sensor nodes structure, current applications of WSNs and critical evaluation metrics for sensor networks are outlined as well as a short description of the protocol stack, network architecture and routing technologies used in WSNs.

Chapter 3

Clustering techniques: Properties, Methods, Objectives and Review

Routing is one of the critical technologies in WSNs and poses challenges for conserving a node's energy (a result of its inherent characteristics). One of WSN's application requirements is to relay information from deployed sensor nodes towards the BS through an efficient routing mechanism [30]. Thus, it is advantageous to utilise hierarchical routing techniques to relay sensor node information [57][22]. Cluster-based routing aims to produce a network to route the information in a hierarchy-based system through several clusters. This chapter presents an overview of clustering approaches in WSNs and outlines cluster properties alongside clustering objectives. In addition, it presents a thorough analysis and discussion of prominent cluster-based routing protocols.

3.1 Overview of Clustering Techniques

As indicated in section 2.7.2 (of the previous chapter), hierarchical routing protocols are typically suitable for large-sized sensor networks that require scalable architecture and efficient resource management [54]. They provide numerous advantages for WSNs such as ensuring high energy efficiency and reliable and stable network architecture and, additionally, allow the health of the network to be monitored and faulty nodes to be easily identified (top-level nodes can play a leading role over low-level nodes) [72]. Networks can also adopt heterogeneous nodes, where some are more powerful or have special capabilities. Consequently, the use of cluster-based approaches significantly improves the short network lifespan according to various proposed algorithms [18][63].

With respect to the trade-off between energy efficiency, packet delivery (Reliability) and stability requirements in most WSNs applications, it is clear that WSNs benefit a great deal from hierarchical architecture by promoting manageable forms that can substantially decrease and load-balance the management overhead. Thus, researchers have proposed various clustering schemes aimed at achieving different objectives within the context of the resource management challenges of WSNs.

Generally, cluster-based approaches constitute the process of organising network nodes into a number of clusters. Each cluster has a leader-node identified as the cluster head (CH). The CH is the core node within the cluster, and it regulates data aggregation, fusion and processing, as well as improves bandwidth usage. Other nodes within the cluster are referred to as cluster members (CM); these nodes sense physical phenomena data and transmit the collected values to the CH which then transmits them across other clusters or to the Base Station (BS). The general system model for cluster-based approaches is depicted in Figure 14. The sensor nodes are identified by their unique local collaboration in cluster structuring. However, the process of re-electing CHs to distribute the load among nodes results in a considerable increase in energy consumption [22].

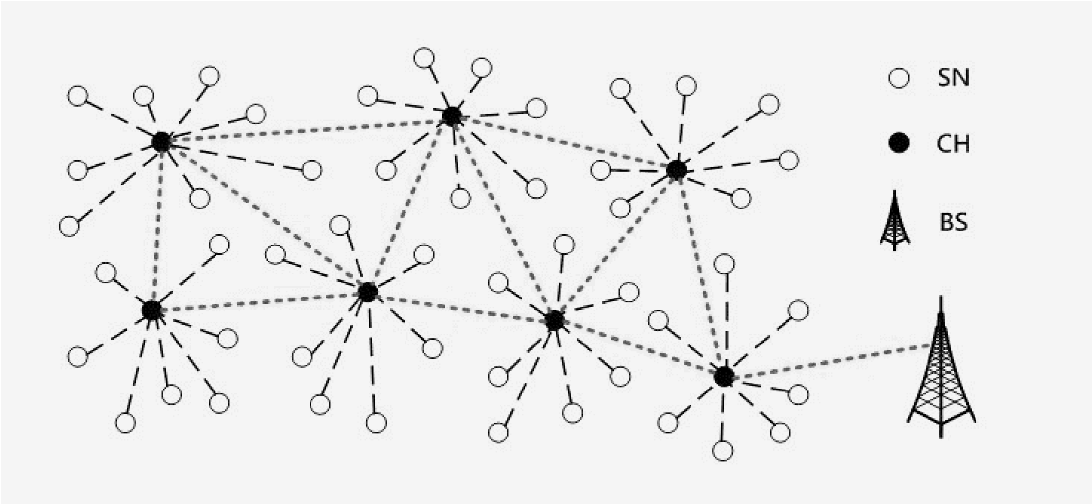

Figure 14: General Cluster-based Architecture in WSNs

Clustering processes can be summarised into three categories: CH election, cluster formation and data transmission. In many sensor applications, the election of the CH is a crucial factor which can affect the performance of the network. In general, the cluster formation can be centralised, distributed or hybridised. In the centralised formation, the CHs are pre-elected by the administrator of the network or BS. The overhead in centralised selections is high due to the lack of local knowledge in this scheme – for example, LEACH-C [73]. However, in distributed clustering, any node in the network can run the algorithm locally and compete to become the CH. The election process is based on specific metrics related to many algorithms such as HEED [74], for example, the residual energy of nodes. The overhead is lower compared to the centralised scheme because the local knowledge available among the nodes is involved in the election process. The hybrid scheme is a combination of both centralised and distributed schemes; while benefiting from both local and global knowledge, this scheme is capable of forming more effective clusters such as in ACE [75] and FLOC [76].

3.2 Taxonomy of Clustering attributes

According to the literature, clustering attributes can be classified into three categories: cluster properties, CH properties and cluster formation processes. The following section summaries the relevant characteristics of the internal structure for the generated clusters (defined as cluster-based approach properties in WSNs).

3.2.1 Characteristics Sensor Network Clusters

***The size of a cluster**:* it can be defined by the proportional distance between the nodes within the cluster. When the distance decreases, less energy consumed by the members as a result of the lower transmission power required to transmit the data [77]. In WSNs clustering architecture, there are two types of clusters, equal clusters and unequal clusters [78]. In equal clustering, the size of the clusters can be proportionally equal throughout the network, whereas, unequal clusters attempts to avoid the hot spot issue [78] occurs in equal clusters size by generating smaller size clusters around the BS. To achieve that, the cluster near BS most have fewer nodes and the node number and cluster size increase as the distance increases. In term of energy consumption, in unequal clusters network, the nodes consume less energy than in equal clusters because it requires less intra/inter-cluster communications [21][78].

***Cluster's Count**:* is referred to as the number of clusters in the network which can be classified into two categories, fixed and dynamic. In several algorithms, the set of CHs is predefined; hence, the clusters produced in the network is fixed. The LEACH algorithm [79] pre-sets five percent of the deployed nodes within the network to become CHs. Thus the number of clusters always fixed. However, in dynamic algorithms, the selections of CHs is based on rules defined by the algorithm, these rules can be the nodes with the highest energy, as is the case in HEED algorithms [74].

Node Density within Cluster: is defined as the proportion of the number of cluster member in the cluster and cluster area. Minimising the energy consumption of CHs in dense clusters is a significant challenge [30]. Some clustering approaches that use fixed clustering always have a sparse density of clusters, but in dynamic clustering approaches, cluster density is variable [30]. In clustering approaches, some characteristics must be taken into account before designing a new algorithm. The following are characteristics that are related to the internal structure of the cluster.

***Connectivity in Intra-Cluster*:** refers to the communication between CHs and its cluster members nodes. This manner of communication can be classified into two categories: single-hop and multi-hop routing communications [80]. In Single-hop manner, the cluster nodes transmit data directly to CH. However, in multi-hop, the cluster nodes relay data to the next node to be transmitted to the corresponding CH; this manner is preferred in large networks with dense nodes.

Connectivity in Inter-Cluster: is the communication between the BS and the CHs. This manner of communication can be classified into two categories: single-hop (direct) and multi-hop (indirect) intra-cluster routing communications [26]. In direct inter-clusters, the CHs transmit the data they gather directly to the BS. In contrast, in indirect routing, the CHs transmits this data via other CHs to send on to the BS.

3.2.2 Attributes of Cluster-Head

***The existence of CH**:* In cluster-based approaches, the CH nodes can exist as in traditional clustering approaches, or the network can be constructed without CHs nodes as in chain-based approaches [81].

Nodes Capabilities: in cluster-based approaches, the deployed nodes can be homogeneous or heterogeneous depending on network application [26]. If the deployed nodes are homogeneous, all the SN are assigned with equal capabilities such as initial energy, processor, and transmission range, The CHs are designated randomly or based on some other criteria. However, in homogeneous networks, the nodes are assigned different capabilities.

Node Mobility: In a cluster-based network deployment, the nodes can be stationary depending on the application; on the other hand, in some application the nodes have to serve the system with certain movement [82].

The Role of CH: The primary role of a CH within its cluster is to perform aggregation/fusion of the traffic generated by the SN. Moreover, CH acts as the only communication channel between deployed nodes and BS [32].

3.2.3 Constructing Clusters Process

Cluster formation: As discussed in the previous section of this chapter, cluster formation can be centralised, distributed or hybridised. Firstly, in a centralised manner, the global network information for deployed nodes is provided by the BS or network administrator in order to form the clusters. Secondly, in a distributed manner, the global network information is not required by deployed SNs, because the cluster can be formed autonomously by the nodes. Lastly, the Hybridised approach is composed of both centralised and distributed approaches, where the BS can involve in part of cluster formation.

Execution of cluster-based algorithms: the cluster-based algorithm of WSNs can be executed probabilistic manner or non-probabilistic manner [83]. In a probabilistic manner, the nodes in the network compute a probability value to determine its role in the network whether the node becomes CH or cluster member. On the other hand, non-probabilistic manner, each SN can independently decide its own roles based on algorithm criteria for CHs election and cluster construction process.

Algorithm Convergence Time*:* convergence time of cluster-based methods for WSNs can be variable where the total number of deployed SN within the network affects the convergence time, accordingly, a variable method suitable for the small size. In contrast, the convergence time can be constant, which is suitable for large scale network [84].

Algorithm Proactivity: In WSNs cluster-based, the algorithms proactive, reactive, or hybrid algorithm [85]. According to proactive algorithms, the collected data routed from deployed SN to BS in pre-determined paths. Unlike proactive the reactive algorithms, the SN will determine the path depending on the applied method. Moreover, in WSNs algorithm can be hybrid, which combines proactive and reactive approaches. The hybrid approach is used in APTEEN [86].

3.3 Clustering Objectives

3.3.1 Support Scalability

In WSNs, the protocol is said to be scalable if it can accommodate an increasing number of nodes or increasing the workload on the network [41]. Clustering is effective in improving the scalability in WSNs by localising the route set up within the cluster [57]. Compared with a flat topology, clustered networks are easy to manage and could scale better.

3.3.2 Effective Data Aggregation

Data aggregation and fusion in WSNs algorithms is very important to reduce the number of communication packets transmitted from SN to BS [26]. Thus, the redundant data can be eliminated, which can result in extending the network lifetime. In constrained SN, it is inefficient to transmit the data directly to the BS [87]. Instead, the nodes can transmit data to a local aggregator or CH, which then aggregates the data and transmits it to the BS.

3.3.3 Reduce Overall Energy Consumption

The network lifetime can be increased by employing data aggregation in order to reduce the total number of packets involved in routing to the BS and eliminate redundant data within the cluster [9]. Moreover, the use of the multi-hope method can mitigate the energy consumption caused by the use of the maximum transmission range by the node to deliver their data to BS [63].

3.3.4 Reliability

In conventional wireless networks, packet collision can affect the reliability of the network and, more importantly, waste network resources [30]. In WSNs, this effect can be worse because, in many applications, the nodes are deployed in large numbers, causing burst-traffic and congestion around the BS [25]. Consequently, significant problems occur that can affect the performance of the whole application. The clustering model in WSNs offers better topology management by dividing the network into clusters and data transmission into different levels. Consequently, it reduces data collision within the network and between clusters.

3.3.5 Latency Reduction

The clustering model aids seamless data to flow from the cluster member nodes to CHs where data aggregated before being transmitted to the BS. This process avoids collisions between the nodes and reduces latency. Furthermore, CHs are the only nodes that perform data transmission across the network, reducing the number of hops to reach the BS and also decreasing latency [42].

3.3.6 Extending Network Lifetime

The most crucial requirement for most of WSNs applications is maximising the network lifetime by considering nodes limited resources. According to [19] in some cases, the CHs have higher energy capacity than cluster member nodes; therefore, it is not practical to only minimise energy consumption for intra-cluster communication. Because the nodes that become CHs should be placed closest to the sensor nodes to reduce the transmission range. Moreover, in inter-cluster communications, selecting the routes where nodes have more energy to relay data can prolong the network lifetime.

3.3.7 Robust Quality of Service

Many WSNs applications have substantial requirements for end-to-end delay and losses during data transmissions [80]. These requirements are referred to as Quality of Service (QoS) but are characterised by some issues. QoS parameters are used mostly in WSNs algorithms to analyse the end-to-end delay between the source node and the destination node.

3.3.8 Load-Balancing within Network

Distributing the load among network nodes is essential if the network lifetime is to be prolonged in WSNs. In cluster construction, the distribution of SNs among the clusters is an essential aspect of load-balancing. In general, adopting effective rotation techniques for selected CHs before they deplete their energy will help to prolong the network lifetime [88].

3.3.9 Fault Tolerance Networks

The most important aspect of designing WSNs algorithms is to preserve the deployed node's energy as long as possible [35]. Because of the nature of SNs random deployment, sometimes losing some sensor nodes is inevitable due to environmental impacts or hardware/software failure. The BS is also prone to failure due to hardware/ software failure, or by external and internal attacks [81]. Hence, the WSNs should be able to tolerate fault [89]. In order to achieve fault-tolerance and avoid the loss of significant data, clustering is recommended in these kinds of applications [13]. Re-clustering of the sensor network is an effective method in recovering the network.

3.3.10 Routes Connectivity

In general, WSNs cluster-based routing, the data is transmitted either in single-hop or multi-hop routing. The data delivery to the BS is determined by the connectivity among the nodes in the network [90]. The nodes that are isolated and have no next-hop node to forward their data in some case it cannot perform any routing tasks [49]. Therefore, connectivity is the indispensable requirement for WSNs. The manageable architecture of cluster-based routing offers a great deal in guarantying connectivity compared with flat routing.

3.4 Review and Analysis of the Most Prominent Cluster-Based Algorithms in WSNs

This section presents a review of the most prominent cluster-based algorithms proposed for WSNs and highlight their features with advantages and disadvantages.

3.4.1 Cluster Formation Based Algorithms

3.4.1.1 LEACH

Heinzelman et al. proposed the Low-Energy Adaptive Clustering Hierarchy (LEACH) [79], is the earliest cluster-based algorithms for WSNs, which inspired many successive clustering algorithms. The basic idea of LEACH is to select a set of nodes randomly within the network as CHs in each round so that the nodes with high energy levels will have more opportunity to become CHs.

The LEACH algorithm constructs the cluster in the basis of rounds where each round has a set-up and steady-state phase. The algorithm starts by set-up phase where the CHs are elected, and clusters formed. On the other hand, the steady-state phase involves communication and transmitting data from SNs to the BS by CHs nodes. During the set-up phase, the selection of CHs is distributed, and the nodes in the network have an equal chance in becoming a CH; in the second round, the network will re-select new CH. The nodes can autonomously decide to become a CH or not by employing a CH percentage suggested by the LEACH algorithm. In each round, the nodes compete to become CH by generating a random number ranging from 0 to 1 to be compared with LEACH threshold. If the number generated is less than the threshold, the node will become CH; otherwise, it joins the nearest cluster. This threshold is described by equation 1.

$$T(n) = \begin{cases} \dfrac{P}{1-P\left(r \bmod \dfrac{1}{P}\right)}, & \text{if } n \in G \\ 0, & \text{otherwise} \end{cases} \qquad (1)$$

where *P* represents the generated CH's probability percentage and the *r* value is the network round. The nodes that not been as CH in previous rounds are represented by *G*. Once the CHs nodes are selected, then will broadcast an advertisement message across the network declaring their new role. The nodes that failed to become CH will wait until they receive the broadcast to decide which cluster to join, based on the received signal strength RSSI. The nodes will send back membership messages to the closest CH. The role of CHs rotates periodically among the nodes in order to distribute the energy load. In the steady-state phase, inter-communication takes place, where the cluster members forward collected data to their designated CH. The CHs performs data aggregation from respective clusters and transmit it in a one-hop manner to the BS. The LEACH algorithm reduces routing traffic collisions by employing TDMA for time-slot-scheduling. Figure 15 demonstrates the general LEACH topology.

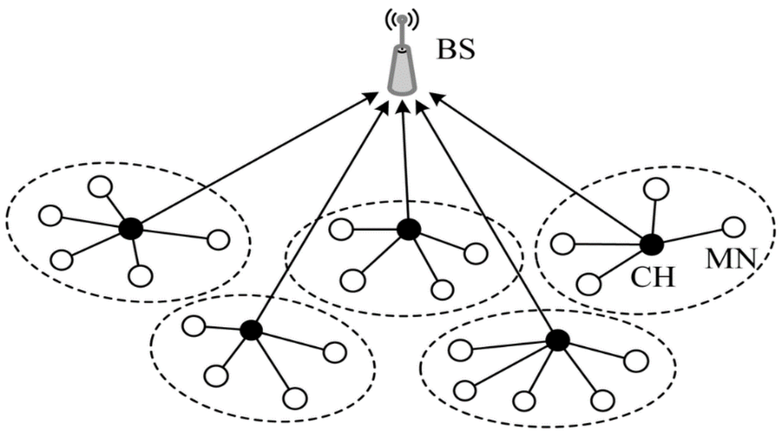

Figure 15: LEACH Protocol Topology Structure

In the literature, the LEACH inspired various algorithms that attempted to improve energy consumption, these modified versions include: *T-LEACH [62], E-LEACH*

VLEACH [59], [56], LEACH-FL [60], LEACH-C [58], M-LEACH [57], W-LEACH [61], L-LEACH [19].

Advantages:

(1) The nodes can become CH only once until all the nodes in the network have been as a CH, so the load among the nodes is shared to some extent.

(2) The collision in inter/intra-cluster communication is reduced by utilising a TDMA schedule.

(3) The cluster member nodes can switch their interface to send data or not by time-slot-scheduling introduced in intra-cluster communication, which helps to preserve the node's energy.

Disadvantages:

(1) One of the main drawbacks of the LEACH algorithm is that it is not applicable for large size networks due to single-hop inter-cluster communication. Utilising the single-hop method poses excessive energy dissipation.

(2) Energy holes and coverage problems are not well considered in LEACH because it performs probabilities of CH selection. This can be problematic when the nodes have different initial energy. When a node with lower energy becomes CH, there is a high possibility that the node will die before the new round begins.

(3) The distributions of CHs throughout the network is not guaranteed under the LEACH algorithm due to probability selection of the CH. There is

always a chance that the selected CHs will be close to each other, which can result in network distribution issue.

3.4.1.2 HEED

Younis and Fahmy presented, Hybrid Energy-Efficient Distributed clustering (HEED) [74], it differs from the LEACH algorithm in CH selections criteria and in inter-cluster communication, where multi-hop is used to route the data from clusters toward BS. Utilising multi-hop manner in HEED enhanced the energy consumption compared with LEACH where it uses a single-hop manner. The CH selection in HEED algorithm is considered by two metrics: node remaining energy and the cost of intra-cluster communication. Those selected CHs in the HEED algorithm have high energy levels within the network. Moreover, these rules are reflected in the distribution of CHs throughout the network. The percentage of selected CHs in the HEED algorithm is based on the following probability equation 2:

$$CH_{prob} = C_{prob} \frac{E_{residual}}{E_{\mathrm{m}}}, \qquad (2)$$

where CH_{prob} is the probability value for the node, $E_{residual}$ represents the remaining energy of the node, and E_{max} represents the maximum energy level for each node. In HEED, the nodes perform several iterations in order to find a CH to join; otherwise, the node declares itself as CH.

Advantages:

(1) HEED algorithm is fully distributed approach where the nodes autonomously form the network.

(2) To some extent, the load balancing in HEED is achieved by selecting CHs with high energy.

(3) Inter-cluster communication is based on multi-hop manner, which enhanced energy-efficiency in contrast with the single-hop fashion.

Disadvantages

(1) The HEED algorithm selects a number of nodes as tentative CHs which, in some cases, means these nodes are forced to qualify for final CHs rule, which can result in having more than one CH within the same range and effects the balance of energy consumption within the network.

(2) The re-clustering process in HEED, which is similar to the process in LEACH, imposes excessive overheads in the network.

(3) Another major overhead issue in HEED is generated by the process of repeated iterations in the construction of clusters. At each iteration, many packets are broadcasted.

(4) The HEED algorithm does not consider the hot spot issue of equal clusters, where the clusters near the BS suffer extreme loads due to handling traffic from far away clusters.

3.4.1.3 DWEHC

Ding et al. Introduced, Distributed Weight-based Energy-efficient Hierarchical Clustering algorithm (DWEHC) [91] The DWEHC and HEED approach are similar in term of CHs selection procedure. The prime goal for DWEHC is to improve intra-cluster communication and balance the constructed clusters. This is achieved through the location awareness technique employed. As in HEED, the residual energy of the node is considered as the main criteria in selecting CH. In contrast to the HEED algorithm, DWEHC generates different intra-cluster communication structure by setting multi-level data traffic flow. Additionally, DWEHC defines weight parameters as the main metric for selecting CHs. The weight is calculated according to equation 3:

$$W_{weight}(s) = \frac{E_{residual}(s)}{E_{initial}(s)} \times \sum_{u} \frac{R-d}{6R} \qquad (3)$$

where $E_{residual}(s)$ represents the remaining energy of deployed sensor node s, $E_{initial}(s)$ is the initial energy of the node s; the cluster range is represented by R while d refers to the distance between neighbouring nodes u. The node with greater weight-value among its neighbour become CH where non-CH join the nearest cluster as a cluster member. Figure 16 illustrates the DWEHC general structure of multi-level clusters. In DWEHC clusters, there are two types of cluster membership, level one and level two membership. Once the node joins the cluster, it is a level, one member. It then decides whether it will remain at level one or change to level two by computing the distance to CH. If the node needs to consume more energy to deliver its data, it will switch to level two. As in HEED, TDMA is utilised in the DWEHC algorithm to perform intra-cluster communication.

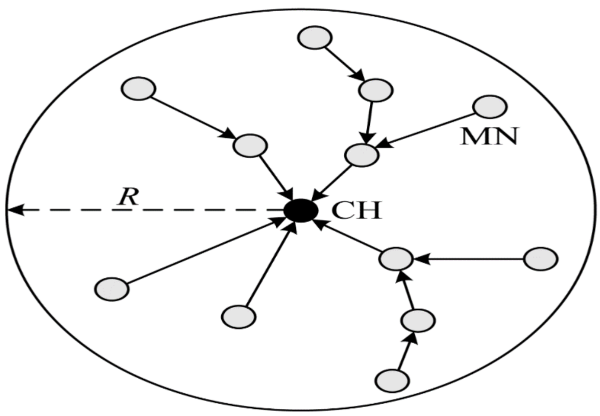

Figure 16: DWEHC Protocol multi-level Structure

Advantages*:*

(1) The DWEHC is fully distributed approach because the nodes can decide their role independently.

(2) The multi-level structure in DWEHC forms better-balanced clusters than HEED in terms of CHs distribution and conserving a node's energy.

(3) Compared to the HEED algorithm, the overhead messages are reduced by lowering the iteration process.

Disadvantages:

(1) The main drawback of DWEHC is the use of the inter-communication method, where the CHs transmit cluster data to the BS on one-hop manner.

(2) Due to direct communication between CHs and the BS, the DWEHC is not suitable for large scale networks (3). Compared with other new clustering algorithms, the DWEHC generates many of overhead messages during the iterative process that constructs the clusters.

3.4.1.4 PANEL

Buttyan and Schaffer introduced, The Position-based Aggregator Node Election protocol (PANEL) [92], it supports asynchronous applications in WSN, where the BS can acquire the sensed data. The main objective of the PANEL is selecting a reference point in predetermined clusters in order to choose one node to become an aggregator. PANEL is a position-based algorithm for sensor networks, the deployment area of the node is assumed to be known, where the clusters can be predetermined. PANEL achieves this by programming the nodes with geographical information before deployment. PANEL introduces reference point R_j, *a* new concept (*epoch*) for selecting the aggregator. In each cluster *j* is the reference point R_j is computed. The R_j number is computed according to the following equation 4:

$$\vec{R}_j = \vec{Q}_j + \vec{Q} \qquad (4)$$

Where *Q* is the position of the lower-left corner of cluster *j*. In order to map the position of *Q*, the epoch value *e* can be called by the function in equation 5.

$$H(e) = \vec{Q} \qquad (5)$$

Once the R_j is computed, the node with the shortest distance of R_j will become the CH. Figure 17 depicts the geographical clustering in PANEL.

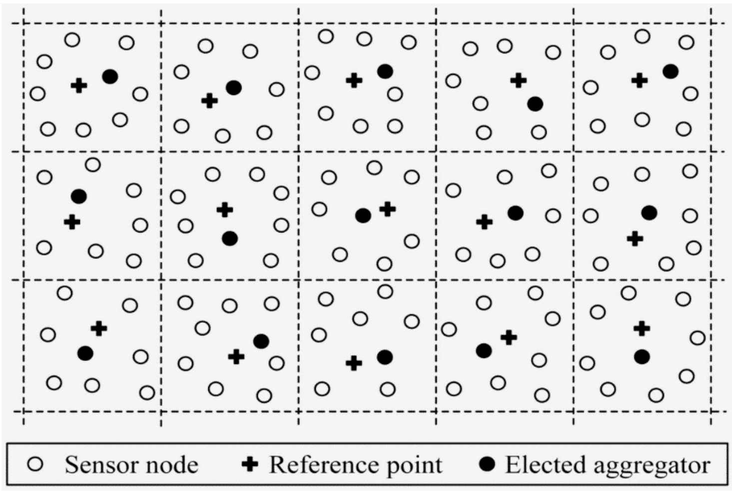

Figure 17: Geographical Clustering Structure for PANEL Protocol

Advantages:

(1) The PANEL is an energy-efficient algorithm that considers load balancing and reduces the communication load by performing data aggregation. These features can ensure a longer lifetime for the network.

(2) The most noticeable benefit compared to other data aggregation algorithm in WSNs is that PANEL supports synchronous and asynchronous applications.

Disadvantages:

(1) The PANEL is a centralised algorithm; it cannot be applied on applications that require dynamic network operation. The centrality issue is based on the predetermination of the clusters before deployment.

(2) Utilising Geographical position software/hardware such as GPS in PANEL is infeasible in many WSNs application as it restricts the flexibility of this network and imposes higher energy consumption.

3.4.1.6 TL-LEACH

Loscrì et al proposed, A Two-Levels Hierarchy for Low-Energy Adaptive Clustering Hierarchy (TL-LEACH) [93], is an extended version of the LEACH algorithm. The main difference to LEACH is that the CHs can transmit their data via top-level CHs. Two-level hierarchy approaches introduced by the TL-LEACH for the cluster formation process. In Figure 18, the top CHs are referred to as top-level CHs, the second layer as secondary CHs and the lower nodes represent the ordinary node. The TL-LEACH consist of four core phases: advertisement, data-transmission-phase and setup/ schedule-phases. During the advertisement phase, the nodes declare their role in the network: whether they will become the main CHs, secondary CHs or ordinary node. The node that self-selects as primary CH must broadcast its role to other nodes across the network. Within the setup-phase, the nodes that declared themselves as secondary CHs will receive the message from the main CH and forward the message to the ordinary node. The secondary CHs will record the path from which the leading

CH received the message and then send a message back informing the primary CH of the relay. In the schedule-phase, the main CHs schedule TDMA slots for each node, thereby informing the nodes when to transmit their data. Moreover, the main CH selects the CDMA code to inform all the secondary CHs in its group to transmit using this code. During the data-transmission-phase, clusters are constructed, and the node can transmit in respect to the TDMA schedule decided by its primary CH.

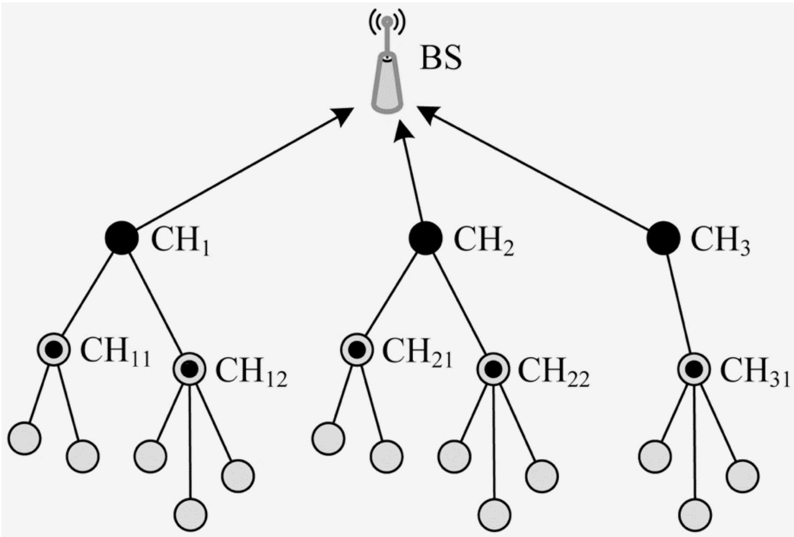

Figure 18: TL-LEACH Protocol Levels Topology Structure

Advantages:

(1) To some extent, the TL-LEACH archives energy load balancing by utilising contracted CH levels and roles throughout the network.

(2) The levels approach used in TL-LEACH provides limited scalability to the network compared with the HEED algorithm.

(3) Communication among the nodes is robust due to the manageable structure of the network.

(4) *In contrast to the LEACH algorithm, direct communication with the BS is reduced because not all the nodes are required to send their data in a hop to the BS, which reduces the energy consumption of the whole network.*

Disadvantages:

(1) *Regardless of the advantages of TL-LEACH in achieving manageable network structure, the lack of multi-hop communications renders it not-applicable to large scale networks.*

(2) *One of the main drawbacks is the random node selection of CH, where the nodes with low energy level can be selected.*

3.4.1.7 UCS

Soro and Heinzelman proposed Unequal Clustering Size (UCS) [94]. The UCS aims to load-balance energy consumed by the nodes and increase network lifetime by organising the sensor network into unequal clusters; it is the first algorithm to classify the sensor network using this structure. The main assumption of UCS is that the CH's position is predetermined, and all the CH nodes must be arranged in circles around the BS. The clusters are organised into two circler layers around the BS, where each layer contains some clusters, as shown in Figure 19. In layer, one has the same size and shape are similar for all the clusters, whereas, in layer two, they are different. In UCS, the energy consumption within clusters can be reduced by positioning the CH should at the centre of the cluster. The predetermined CH's nodes are different from ordinary nodes where the CH nodes have more resources capabilities such as energy level.

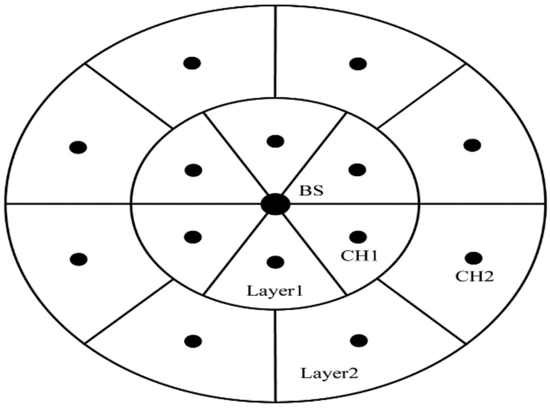

Figure 19: Unequal Clustering Structure for UCS Protocol

UCS assumes the cluster in each layer is constant; however, the cluster can extend its covered area. The data forwarded in UCS multi-hops among CHs until it reaches the BS.

Advantages:

(1) in contrast with equal cluster size approaches, the UCS achieves a greater reduction in energy consumption among CHs in the network

(2) In UCS, the utilisation of unequal clusters beside two-hop communications among CHs have good advantages in term of reliability and extending network lifetime.

Disadvantages:

(1) UCS is constrained by its feature of centralised control, which determines the CH node locations before the deployment of the node.

(2) Despite the improvement in decreasing the average transmission distance by adding two-hop routing within the network, the two-hop approach developed cannot be used when multi-hop communication.

3.4.1.8 EECS

Ye et al introduced The Energy Efficient Clustering Scheme (EECS) [95]. In general, the clustering procedure in EECS is similar to in the LEACH scheme, since it performs the same direct communication between the CHs and the BS. The basic idea of the EECS algorithm is that several nodes are selected to be CH candidates, which then enter the final CH competition. The candidate nodes will broadcast their remaining energy across the network, and it can be received only by other candidates within the node transmission range. If *s* candidate node does not find another neighbouring candidate with more residual energy, it becomes the final CH. The cluster formation in EECS is different from in LEACH, where the EECS provides more flexibility in the size of the generated clusters. The nodes can join the cluster by considering the CH's workload and the remaining energy.

Advantages*:*

(1) The EECS forms balancing communication between the energy and load in the network through intra/inter-cluster communications.
(2) Compared with the LEACH algorithm, the EECS addresses the problem of the long transmission range and the energy required for those clusters that are more distant from the base station.

Disadvantages:

(1) In EECS, nodes consume considerable energy due to performing single-hop, inter-cluster communications. EECS is, therefore, cannot be applied in large size sensor networks.

(2) *EECS produces excessive messages overhead. Due to the global knowledge requirement of the network. The number of messages effects node energy.*

3.4.1.9 EEUC

Li et al, proposed, well-known Energy-Efficient Unequal Clustering (EEUC) [96], is another well-known unequal clustering algorithm that is fully distributed. The CHs are selected among the nodes by local competition, where nodes have a limited competition range, which is smaller for the nodes within a short distance of the BS. This process generates an unequal clustering structure for the purpose of balancing the load between clusters and the node's energy. The nodes in EEUC generate a random value if threshold value if less than the arbitrary value of the node; it will qualify for CH selection. The qualified node broadcasts a message declaring that it will compete for CH. The message can be received only within the node's radius that can be determined by equation 6:

$$s_i.R_{comp} = \left[1 - c\frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}}\right]R^0_{comp} \qquad (6)$$

where R_{comp} is the node competition radius, d_{max} and d_{min} values represent the maximum and minimum of nodes and $d(s_i, BS)$ is the BS distance from node s_i. The c is a constant coefficient range from 0 to 1. By employing the equation 6, the structure of the network will have small clusters near the BS and the size increase when the distance increase. Figure 20 shows the unequal clusters structure in EEUC.

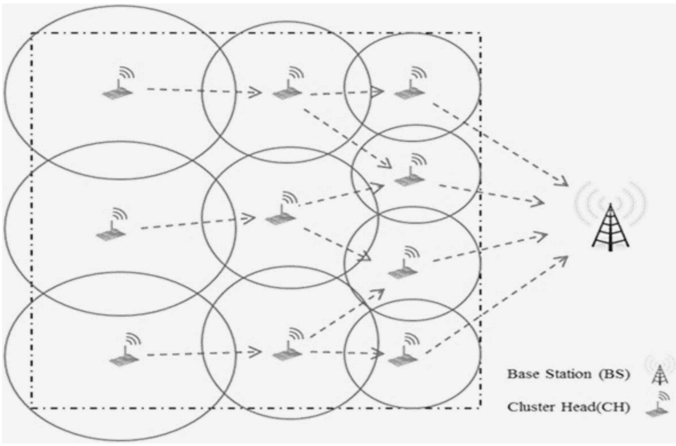

Figure 20: Unequal clusters Structure for EEUC Protocol

Advantages:

(1) EEUC addresses the hot spot problem by introducing an unequal cluster approach in order to balance and reduce the energy consumption among the nodes.

(2) The proposed approaches in EEUC improve the network lifetime more than do the LEACH and HEED algorithms.

(3) In EEUC employing a multi-hop manner, helped to preserve more nodes energy. This is achieved by the mechanism that allows the CH to choose its relay node to forward the cluster data to BS.

Disadvantages:

(1) The process of forming clusters in each round imposes a significant overhead due to the high number of messages involved in final CH competition.

(2) Due to the number of control messages that are used in EEUC which result in increased overheads for all nodes

3.4.1.10 BCDCP

Muruganathan et al introduced, The Base-Station Controlled Dynamic Clustering Protocol (BCDCP) [97], is a centralised cluster-based algorithm. In the BCDCP cluster formation stage, each CH serves a similar number of cluster member nodes to balance the CH overload and create uniform CH placement throughout the network. At the beginning of the clustering process, all the sensor nodes in the network send their residual energy to the BS. Based on received messages from the nodes, the BS performs average residual energy computation and then selects a number set of nodes with high residual energy as CHs. According to the clustering process in BCDCP, the network will be divided into two sub-clusters, and these sub-clusters are divided into more clusters until the desired clusters number in the network is achieved.

Advantages:

(1) The BCDCP achieves energy load balancing by distributing the nodes among the clusters in a similar number.

(2) The network in BCDCP adopts multi-hop communication for better reliability.

(3) The BCDCP uses TDMA to schedule the time in which the cluster member transmits their data to the designated CH.

Disadvantages:

(1) The centralised selection of CHs in BCDCP limited its scalability in large-scale networks.

(2) Due to the requirement of the nodes to send the information to the BS, the energy consumption increases among the nodes, where this can be avoided.

3.4.2 Cluster Data Reliability-Based Algorithms

3.4.2.1 PEGASIS

Lindsey et al proposed Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [98]. The core idea of PEGASIS is that the nodes can transmit their data to the next-hop node, which considered as its parent node in the chain. The nodes are organised to route the data as a chain, as shown in figure 21, the construction of the route can be decided by the nodes independently of by network admin. In order to form the chain by the nodes, the location data of other nodes is required, and the chain must be computed locally. The chain construction starts from a top-down to a top-up manner, where the nodes that are the furthest from the BS start the formation, followed by the closest neighbour to this node in the chain.

The process of gathering and forwarding data in PEGASIS starts from the first node that has data which then forwards the collected data to the next-hop node in the chain. The node that receives the data will fuse it with its own data and forward it to the next-hop toward the BS. This process is repeated until the leader node receives the fused data from all chain members and transmits it to the BS. In order to enhance the robust failure in the PEGASIS algorithm, the leader can die at any given location. Figure 21 represents the data transmission scheme in PEGASIS

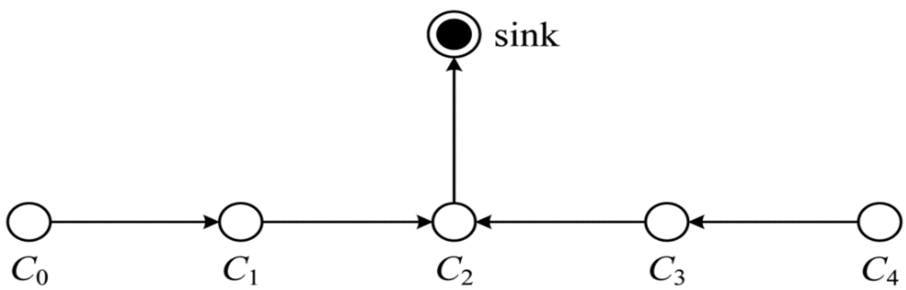

Figure 21: Data Transmission Scheme for PEGASIS Protocol

Advantages:

(1) *The PEGASIS algorithm reduces the overall control messages involved in forming the chain compared to cluster formation in the LEACH protocol.*

(2) *The energy consumption is distributed by the chain construction in the top-down to top-up manner.*

Disadvantages:

(1) *In time-varying topology networks, routing data via the chain is not a suitable approach [71].*

(2) *The use of next-hop routing in the chain reduces energy efficiency and can result in considerable delay.*

3.4.2.2 TEEN

Anjeshwar and Agrawal introduced The Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [99], is the first hierarchical algorithm for reactive sensor networks. The TEEN algorithm operation is presented in Figure 22. The clustering topology consists of two levels: clusters level and CHs level. Hard and Soft thresholds are introduced in the TEEN algorithm. The Hard-threshold represents the value of the sensed event data where the node needs to wake-up and transmit its data to designated CH. On the other hand, a CH can send data to its members through both a hard/soft threshold. The former hard-threshold is triggered when the nodes need to transmit their data, reducing data communication. Conversely, the soft threshold can only be triggered when there is no change in the data type being transmitted.

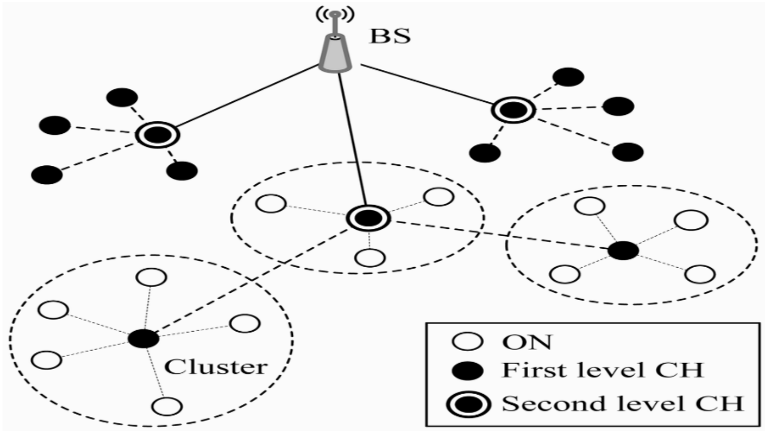

Figure 22: The TEEN Protocol Routing and Topology Structure

Advantages:

(1) The TEEN can control the data transmission by utilising the two thresholds in order to mitigate the energy consumed by the nodes while transmitting their data.

(2) The TEEN algorithm can be used for different application with different requirements in term of sensing.

Disadvantages:

(1) In some applications where periodic reporting is required, the set of thresholds is not suitable.

(2) In random deployments, the CHs can be far away from each other; this can result in data being lost because the CHs are the only nodes responsible for information propagation.

3.4.2.3 APTEEN

Manjeshwar and Agrawal introduced, The Adaptive Threshold Sensitive Energy Efficient Sensor Network protocol (APTEEN) [86], which aims to overcome the original version drawback of TEEN approach. The main issues APTEEN focuses on is how to process a user's query and how to route the needed data. APTEEN classified the query system into three query types: on-time query, historical queries, and persistent query. APTEEN supports QoS by employing TDMA scheduling.

In APTEEN, once the CHs are selected, the following four parameters are broadcasted: (1) Attributes (2) Thresholds (3) Schedule (4) Count time. The APTEEN algorithm the nodes are capable of switching from being proactive to reactive in order to send data to the destination node. Furthermore, the nodes continuously sense the data and only allow data-transmission if their data value is beyond the threshold.

Advantages:

(1) APTEEN combines the proactive features of LEACH and the reactive features of TEEN. Accordingly, it is suitable for both proactive and reactive applications.

(2) TEEN offers a lot of flexibility, by allowing the user to set the count-time interval and the threshold values for energy consumption.

Disadvantages:

(1) Two of the main drawbacks of APTEEN are the threshold functions complexity as well as the count time.

(2) The APTEEN algorithm suffers from excessive overhead generated by cluster construction in a multiple level process and the implementation of threshold-based functions [74].

3.4.2.4 TTDD

Luo et al presented The Two-Tier Data Dissemination (TTDD) [100]. The TTDD proposes to address the problem of multiple mobile sinks and data delivery. TTDD is based on a grid structure routing method. The nodes in TTDD are capable of building a grid structure and set up forwarding information proactively. In TTDD, the grid is constructed by dividing the network domain cells where each cell can be in a square shape, as shown in Figure 23.

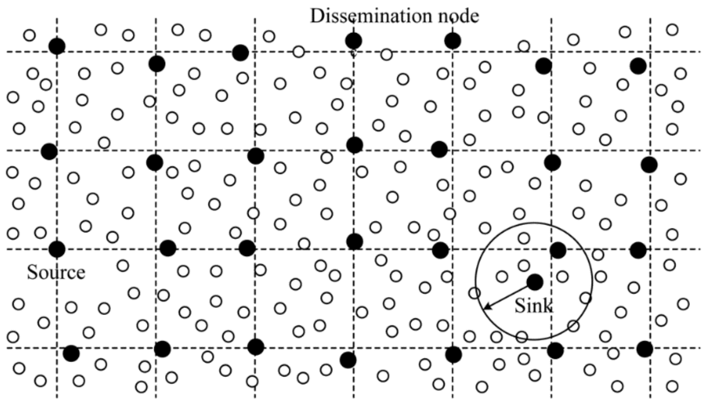

Figure 23: The Two-Tier Data Dissemination Scheme for TTDD Protocol

Advantage:

(1) TTDD offers significant improvements in dealing with multiple mobile BS for a sensor network that requires a scalable structure.

(2) The TTDD approach approved that it's suitable when the mobility of the node is high.

Disadvantages:

(1) The forwarding path in TTDD may lead to significant latency as it is not the shortest path to deliver the data.

(2) The energy consumption is high due to the grid construction and query flooding technique used.

(3) Utilising GPS is not advised in WSNs as it can have negative impacts on sensor nodes.

(4) In TTDD, maintaining the structure generates extensive overhead.

3.4.2.5 HGMR

Koutsonikolas et al proposed Hierarchical Geographic Multicast Routing (HGMR) [101], is a location-based multicast algorithm that seamlessly integrates with the key design of (GMR) [102] and (HRPM) algorithm [103]. HGMR starts by using mobile geographic hashing introduced in HRPM to generate the small manageable group. The local multicast approach of GMR is assumed by HRPM in order to transmit the data along the multicast tree. The deployment domain of the network is divided into a number of cells, where the Access Point (AP) is used to manage the cell member, where the Rendezvous Point (RP) manages all the AP. Figure 24 presents network structure and data delivery in HGMR.

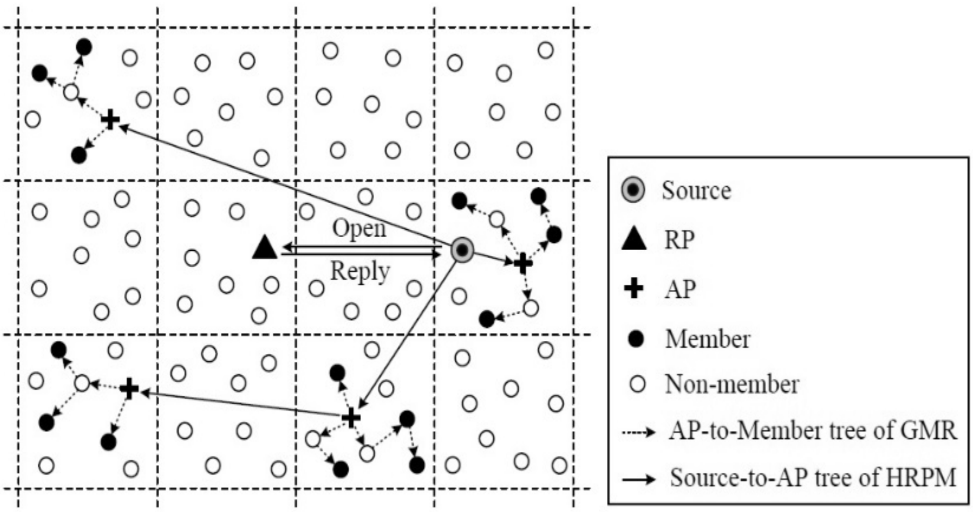

Figure 24: Network Structure and Data Delivery for HGMR Protocol

Advantage:

(1) The use of a Geographic Hashing Algorithm used in HGMR to manage the significantly improved data transmission without any extra cost in term of energy consumption.

(2) The data routing in HFMR is effective for QoS and reliability of sensor networks.

(3) HGMR is a scalable algorithm due to the manageable cell offered.

Disadvantage:

(1) In some scenario utilisation of AP effects, the load balance within the network.

(2) To some extent, HGMR makes the routing paths inefficient, by the complexity of AP levels.

3.5 Conclusion

This chapter has deliberated and reviewed the clustering techniques in order to pave the way for this research. The main concepts related to clustering are outlined, i.e. (Taxonomy of clustering attribute, the objective of clustering technique and detailed review of the most prominent algorithms for WSNs). In addition, the chapter has identified the critical limitations for each mechanism proposed by the research community and highlighting the major drawbacks in existing clustering. Hence, the chapter concludes that the existing clustering mechanisms suffer from three major gaps and novel mechanisms have been developed in this thesis that addresses such gaps.

The first gap identified in this context is the lack of an efficient cluster-head selection method that is energy-aware and reduces a rapid energy depletion of CH nodes that handle the load of excessive traffic. The energy holes and coverage problems are not adequately addressed because most of the existing efforts perform probabilities of CH selection, where the CH nodes randomly selected. This can be problematic when the nodes have different initial energy. When a node with lower energy becomes CH, there is a high possibility that the node will die before the new round begins. Furthermore, some algorithms perform a centralised manner to select a CH node; this cannot be applied to some applications that require dynamic and autonomous network operation. The centrality issue is based on the predetermination of the clusters before deployment. To fulfil former gaps, A New Dynamic Weight-Based Clustering Algorithm for Wireless Sensor Networks has been introduced in Chapter 4.

The second gap being identified concerns the lack of reliability and the load-balancing of the clusters that ensures a fair distribution of load among the nodes while minimising overhead and maintaining network stability. In the reviewed algorithms in section 3.4.1, the distributions of CHs throughout the network is not guaranteed due to probability selection of the CH. There is always a chance that the selected CHs will be close to each other, which can result in network distribution issue. Moreover, another gap identified is the use of the inter-communication method, where the CHs transmit cluster data to the BS on a one-hop manner. Due to direct communication between CHs and the BS, this method is not suitable for large scale networks in term of data forwarding and reliable communication. Additionally, the excessive number of generated messages to construct clusters have a negative impact on nodes limited energy. To fulfil former gaps, a new Weight and Energy-Efficient Rotating Clustering Protocol have been designed as presented in Chapter 5.

The third significant gap identified concerns the lack of efficient data routing that addresses the hot spot issue of equal clusters, where the clusters near the BS suffer extreme loads due to handling traffic from far away clusters. The process of forming clusters in each round imposes a significant overhead due to the high number of messages involved in final CH competition. Due to the number of control messages that are used, which result in increased overheads for all the nodes. Some of the existing mechanisms reviewed in section 3.4 utilise GPS for locating the node's position this is not advised in WSNs as it can have negative impacts on sensor nodes limited energy. Maintaining the network structure generated have not been well addressed in the literature, particularly with cluster-based mechanisms. In response, Reliable and Energy-Efficient Two-Level Unequal Clustering Mechanism for WSNs has been proposed as illustrated in Chapter 6.

Chapter 4

A New Dynamic Weight-Based Clustering Algorithm for Wireless Sensor Networks

In chapter 3, clustering properties, methods, objectives, and analyses of prominent algorithms were presented. This chapter discusses a *New Dynamic Weight-Based Clustering Algorithm for Wireless Sensor Networks (DWCA)* [112], which extends the network lifetime through a combination of metrics with the aim of electing an optimal Cluster-Head and balancing the energy consumption among all nodes. In this chapter, Section 4.1 begins with some background and revisits the issues inherent in selecting Cluster-Heads using existing algorithms. Section 4.2 gives an overview of the stated problem, while section 4.3 provides a detailed description of *DWCA*. Implementations, an analysis and performance evaluation are provided in section 4.4.

4.1 Introduction

One of the most restrictive factors of sensor networks is the limited energy resources of the deployed nodes [63] [104], which means that extending the sensor node lifetime is an important factor for WSNs. Thus, considering the node's scarce resources, it is vital to design a new energy-efficiency algorithm for WSNs. In order to achieve high energy-efficiency and assure the long lifetime of the network, the sensor network can be partitioned into manageable sections. Sensor nodes can be organised into clusters, where sensed data is collected and processed locally as autonomous clusters before being sent to the BS. In many sensor network applications where the lifetime is crucial, the hierarchical mechanism appears to be a promising scheme for efficiently organising the network. However, unbalanced energy consumption among clusters is still considered a problem in the current literature, and it is tightly bound to the selection of CH nodes within the network [89][105][106]. Compared with ordinary nodes in the cluster, CH nodes consume more energy due to frequently receiving data from cluster member nodes and having to aggregate and transmit data to other CHs or directly to the BS [63].

The number of cluster member nodes, as well as the distances between CH nodes and the BS, can also affect energy consumption in WSNs [104]. In addition, in some cluster-based applications, the network is organised into heterogeneous clusters, where some more powerful nodes take on the CH role in order to control network operation; it is important to ensure that the energy dissipation of these CH nodes is balanced [107]. Hence the selection of CHs can determine the lifetime of WSNs [108]. Selecting an optimal node for the CH role is very important in order to effectively balance the energy consumption among nodes and avoid the premature failure or death of CH nodes.

Clustering has been a popular area of research due to a number of advantages it offers (see chapter 3, section 3.3). Although significant research effort has been invested in creating clustering algorithms for sensor network so far, there are still some challenges that confront effective solutions in clustering mechanisms. The critical issues of existing algorithms are inherent in the selection of CHs [109][22] because some aspects of system functionalities are not considered when selecting CH in random deployment application [110] [111]. The DWCA tackles the hotspot problem of selecting optimal CH nodes [58], providing an energy-efficient method for WSNs. Unlike the previous examples reviewed in chapter 3, CH nodes in DWCA are selected mainly by considering the node's residual energy, location within deployment filed, and the distance from the BS. The following section describes the specific problem that motivated the design of DWCA.

4.2 Problem Outline

Because of the inherent design challenges and characteristics of sensor networks, they cannot be treated like other conventional wireless networks. In WSN's algorithms, the most crucial design factor is energy consumption [113]. The proper design and implementation of a new algorithm on the architecture level are required. Two critical challenges inherent in designing and implementing a new algorithm are the varying topology nature and the node's limited power [114].

As discussed in the previous section, clustering is an effective method for optimising energy consumption and stable network architecture. Many studies proposing methods for clustering sensor nodes focus on different aims in this respect [93][96][115][95][74][116], Some of the previous algorithms introduce probabilistic mechanisms and the periodic reassignment of the CHs role within a randomly deployed node [62]. This strategy helps to prevent the problem of a node failure in the event of energy depletion or external damage [41]. However, using such a mechanism can result in selecting nodes with less energy or that have been elected before for the CH role [18]. Other algorithms set alternate criteria in choosing CH nodes, for example, residual node energy, which is particularly vital since CH nodes have more tasks than ordinary nodes [74]. In such methods, there is a critical limitation in nonuniform deployments, where the high energy nodes can become concentrated in a specific area in the network [54] [117][118].

According to most of the cluster-based mechanisms, in order to form clusters, some nodes have to be selected as CHs in the network. For a graphical representation of the problem, Figure 26 demonstrates sensor nodes randomly deployed in a specific area. The assumption of this example is that the nodes with high energy level will be CHs as in HEED [74], EEUC [96] and LCP [119], against which the proposed DWCA was compared. In random deployment, the nodes can be placed anywhere in the sensing field, although the nodes with high energy level are not known among the nodes. Based on that, the node 1, 2 and 3 may have greater energy level among the nodes. The first issue in this scenario is that node 1 will become CH among all its neighbours.

As can be observed from the figure (25) it is off-centre for that set of nodes, in such cases, all the set of nodes will join in one node to form the cluster and start transmitting their data. The node 1, as it is the CH, it will have to send aggregated data to the BS with maximum transmission power, which will result in draining its energy faster due to the transmission cost to BS. Another problem, which is not considered in the literature for the cluster-based algorithms, is the CHs locations in the first rounds and its distance from the BS. In such cases, the location and distance can mitigate the energy consumption for the whole network if these metrics have been considered in the selection process.

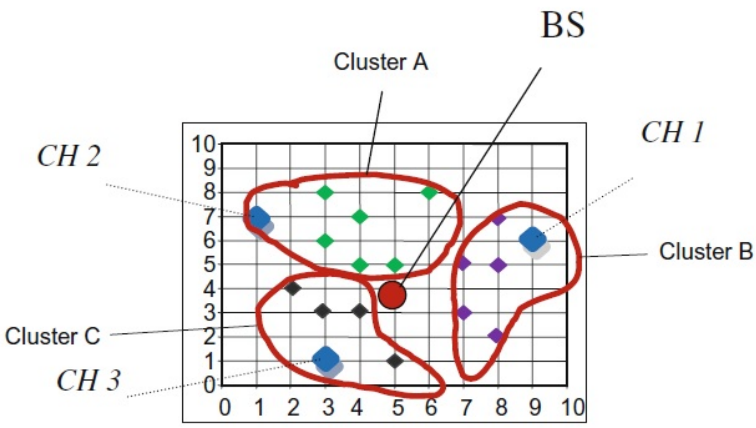

Figure 25: CH Selection Problem in Radom Deployment

The following section describes how the proposed mechanism overcomes the above problem. The experiments results show that the DWCA achieves its aims.

4.3 Proposed Approach

To address the above issues, a new Dynamic Weight-Based Clustering Algorithm for Wireless Sensor Networks (*DWCA*) is proposed. The DWCA has two distinguishing features:

(4) It is a *fully distributed* algorithm where no BS or end-user will be involved in the clusters constructing process. This is one of WSNs critical application requirements, especially when the nodes are randomly deployed, which is the scenario that has been considered in the DWCA structure.

(5) DWCA introduces a new type of *CH candidate* selection to ensure the nodes that become the final CH are distributed throughout the sensing field and that the CH nodes have minimum resource requirements for serving in the CH role.

The DWCA consist of two main phases: the set-up phase and the steady-state phase. The set-up phase can be broken down into the following: initialisation stage, CHs candidate's election and final CHs election. In the steady-state phase, after the clusters are constructed, inter-cluster and intra-cluster communication take place in the network. For a clearer understanding of DWCA operation, more details are presented in the following sections.

The election process is similar to the most well-known clustering algorithms for WSNs (as in LEACH and HEED). The difference is that DWCA the nodes utilises local information available to decide whether to become CH or ordinary node in the network, the local information includes the number of neighbouring nodes "*degree D*", the distance from the BS and mainly the remaining energy of the node "*E*". The DWCA considers these local parameters as the node's *weight*. All the nodes will perform weight calculations locally then each node broadcasts its weight in one single message to its neighbour. Each node will compare its weight with all neighbouring nodes in order to decide which node will be selected among the set of neighbours as the CH candidate. The nodes that become the CH candidate will declare themselves in the network by broadcasting a candidate message containing the node ID and "*CHcandidate =true*" flag to the network. In order to conserve node energy, the remaining nodes will change their status from active to idle until the process of CH selection finishes.

Only the candidate's nodes in the network can hear the message, this to ensure fewer nodes will compete for the CH role and preserve other node's energy. Once all the nodes have received a message from another candidate within its radius, the radius range can be obtained by employing the R_{comp} function. Finally, the candidates will compete within their radius based on the DWCA procedure explained in the next section

4.4 Implementation Procedures

This section describes the steps of the CHs selection procedure. The steps consist of the following:

Input: A set of homogeneous sensor nodes are randomly deployed. The nodes are similar in transmission radius R_v, transmission rate r_v, and initial energy E_v.

Output: A set of cluster head nodes.

STEP 1: Find the neighbours *N[V]* of each node *v*, where a neighbour is within transmission distance R_t:

$$d_v = |N[V]| = \sum_{V' \in V,\ v' \neq v} \{distance\ (V, V') \ \leq R_t\}. \qquad (7)$$

Where *N*[*V*] is the degree of the node v, distance *(v, v')* represent the distance between node v and node v'.

STEP 2: Find the distance of $N_{(v)}$ from the Base Station $BsD_{(v)}$.

STEP 3: The remaining energy E_v is calculated. It indicates how much residual energy a node still holds.

STEP 4: Calculate the combined weight for every node *v*.

$$W_v = w_1 d_v + w_2 BsD_v + w_3 E_v \qquad (8)$$

where $[w_1 = 0.2,\ w_2 = 0.2,\ w_3 = 0.6]\ (w_1 + w_2 + w_3 = 1)$

w_1, w_2 and w_3 are coefficient values that are defined by the user to contribute to each metrics. In this simulation experiments the represented values determined by the assumption that the value of the energy is the most important factor in our evaluation.

STEP 5: Choose the node with a maximum W_V as the *CH candidate*.

- **Initialisation Stage**

The initialisation stage starts once the node is randomly deployed in the area of interest. In the beginning, the nodes in the network will broadcast the *HELLO message* for its neighbour's in the network to discover. A node will listen to the *HELLO messages* broadcast by other nodes and check the number of neighbours.

The node will then broadcast a message stating the *Remaining Energy* and distance to the BS. Once all the nodes have received the *HELLO messages* from their neighbours, each node will calculate its weight (*W*). In the last step of this stage, all nodes broadcast their weight across the network. The below pseudocode represents the initialisation stage of DWCA.

Algorithm 1 Initialisation:

```
1: for each node n ∈ N do
2:     w_Δ ← find neighbouring nodes
3:     w_ε ← Compute Remaining Energy
4:     w_DB ← Compute distance to the base station
5:     W = w_Δ + w_ε + w_DB
6:     Broadcast message (n_ID, W)
7: end for
```

- **The CH candidate's election phase**

In this phase, once the nodes receive a *W* value from the nodes *n*, each node will check its own weight and, if the weight of $n_i > n_j$ and n_i is within the *threshold*, then the node will become a CH candidate. The *threshold* is defined as 20% of the nodes with the highest *W* in the network. The nodes that satisfy the criteria for CH candidacy will declare themselves to be CH candidates in that round. All the CH candidates will broadcast the *COMPETE-MSG* message alongside their IDs. Those that fail to pass the condition will enter sleep mode until the end of the competition process. The following pseudocode presents the selection of a CH candidate.

Algorithm 2 Cluster Head candidate election

for each node $n \in N$ **do**
    if $w_i > w_j$ & n_i within *Threshold* **then**
        CH candidate = TRUE
        $BroadcastCOMPETE - MSG(n_{ID})$
    else
        SLEEP MODE=TRUE
    end if
end for

- **Finalisation Stage**

In this phase, the candidate nodes receive the *COMPETE-MSG* message from other CH candidates. Each node will use the R_{comp} function (as in line 2 of algorithm 3) to check its diameter in comparison with other candidates. If there are no other candidates, the node will become the final CH; otherwise, the node with the greatest weight will become the final CH, and the other nodes will stop competing, even if they share the same diameter. Once all CHs declare themselves, the process of forming the cluster is similar to that in the HEED and LEACH protocols.

Algorithm 3 Final Cluster Head election

1: On receiving COMPETE-MSG
2: **if** $(d(n_i, n_j) < n_j.R_{comp}$ OR $d(n_i, n_j) < n_i.R_{comp})$ **then**
3:     *Add* s_j *to* $s_i.S_{CH}$
4: **end if**
5: **while** $CHcand = TRUE$ **do**
6:     **if** $w_i > w_i$ **then**
7:         IsCH =TRUE then
8:         Broadcast CLUSTER HEAD-MSG (n_{ID})
9:         else CHcand = FALSE
10:         EXIT
11:     **end if**
12: **end while**

4.5 Methodology and Evaluation Metrics

The proposed algorithms have been validated through the process of simulator testing, rather than using actual hardware devices such as sensor nodes and BS. This was due to the complexity of development, and the cost and the consistency of results required. Several sensor network simulators are currently available, which provide options to test the proposed algorithm, some of these simulators include, NS-2 [120] SensorSim [121], TOSSIM [122], OPNET [123]. However, the Castalia simulator [124] has been chosen as the most suitable simulation environment for this research. Castalia is based on OMNeT++ [125], which can be used to evaluate different platform characteristics for specific applications. It can incorporate an arbitrary number of nodes on arbitrary and even dynamic topology. Castalia models all the essential aspects of the communication channel and application.

Key features are: (1) Castalia supports the Channel Model for mobility and route among the nodes within the network. (2) It models a realistic Radio Model and Wireless Channel. (3) Castalia simulator supports most of sensor networks applications; it models all the essential aspects of their communication channel. (4) Several popular router protocols and MAC protocols are implemented, and the RSSI [126] calculation can provide more convincing and accurate simulation results.

Notably, the greater the number of experiments conducted, the more accurate the results can be. Thus, simulation experiments are conducted in order to validate the proposed algorithm. These experiments are based on real application setups and the scenarios assumed for the simulation are based on temperature monitoring in the natural environment through the random deployment of sensor nodes. The aim is to construct several clusters and test the lifetime of the nodes. In such a scenario, the nodes are randomly deployed in the area of interest and can independently construct a network of several clusters and start sensing the change in temperature readings. The nodes will send the sensed data to their designated CH in order to forward it to the BS. Castalia simulator models a realistic Radio Model and Wireless Channel by using a Packet Reception Rate (PRR) based on an experiential model. Castalia simulator uses the Log Distance Path Loss model, along with wireless communication, which provides the Packet Reception Probability (PRP). These guarantees the realistic operation as described by Zuniga. The energy model considered in this research for energy consumption and network lifetime is based on the [96] model. The model uses both free space (d^2 power loss) and multi-path fading (d^4 power loss) for the channel models. Energy consumption is decided dependant on the distance between the transmitter and the receiver. Moreover, Castalia keeps track of the energy consumption of sensor nodes as the linear depletion. Furthermore, the Castalia define other models to measures the values of energy spent by the nodes in receiving, transmitting and sleeping status. In all the contributions of this research, the nodes are considered as static throughout the network lifetime. Hence, the mobility is out of the scope for this research. The resource manager is the responsible module to manage and calculate the energy consumption in Castalia simulator.

4.5.1 Overhead

In order to evaluate the overhead generated by control messages while constructing the clusters, this metric is used to evaluate the number of frequent messages exchanged during the setup phase. The overhead is measured in the proposed algorithm due to its impact on the energy consumption of the deployed sensor nodes [63].

4.5.2 Energy Consumption

Since it is difficult to either replace individual sensor nodes or their batteries in the network, it is necessary to reduce and balance the energy consumption of sensor nodes to increase the longevity of the network [110]. As mentioned in chapter 1, section 2.1, sensor nodes consist of a sensing unit, processor unit and communication unit, which always affect the nodes lifetime. In order to reduce node energy consumption, the new mechanism most consider these units before engaging with the application.

4.5.3 Lifetime of The Network

The lifetime metric for a sensor network is mostly determined by the lifespan of the sensor node in the network [127]. In some cases, the network lifetime is determined by the average number of life node in the network [145]. In this thesis, the network lifetime is computed by three metrics, according to [128] [129]. First Node Dies (FND) when the first node in the network has depleted its total energy. Last Node Dies (LND), is when all the nodes in the network have consumed their total energy and the network assumes inactive. Besides measuring the lifetime of the network, the scalability of the network is assumed in the following experiments results. In the following experiments, the network is assumed to have a total number of nodes from 200 to 500.

4.5.4 Reliability

One of the WSNs application is to guarantee the delivery of messages to the BS or end-user. Therefore, in this thesis, the reliability of the network is evaluated by computing the number of messages generated by the nodes and the number of messages received by BS [130].

4.6 Experiments and Results

In order to evaluate the performance of the DWCA [112], experiment results were compared against the LCP [119], EEUC [96] and HEED [74] algorithms. As previously discussed, the experiments were conducted using the Castalia simulator, which is based on the OMNeT++ platform. The simulation parameters considered for these experiments are shown in table 1:

Table 1: Simulation Parameters and Values for DWCA, LCP, EEUC and HEED.

Parameter	Value
Deployment domain	150 m x 150 m
Deployment method	Uniform, random
Simulation time per second	500–1100
Deployed nodes	200, 250, 300, 350, 400, 450, 500
Initial energy	25 J
Nodes status	Stationary
Application	Throughput test
Base Station location	Central
Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	DWCA, HEED, LCP, EEUC

Minimising unnecessary control messages during the set-up phase is required in the cluster-based algorithm to assess its relationship with the energy consumption of sensor nodes. Accordingly, a number of experiments carried out to evaluate the DWCA [112] (*Setup messages overhead*) against the HEED [74], LCP [119] and EEUC [96]. Table 1 represents the simulation setting for the conducted experiments for networks with nodes ranging from 200 nodes up to 500 in an area of 150m x 150m. As can be seen in figure 26, the DWCA has fewer control messages over different scenarios, while HEED and EEUC, had the highest control messages in all the scenarios because both algorithms perform a long iteration process during the set-up phase. On the other hand, the technique used in *DWCA* to select a number of CHs candidate and then allowing the remaining nodes to switch to sleep mode achieved a better result in reducing the messages exchanged at the set-up phase.

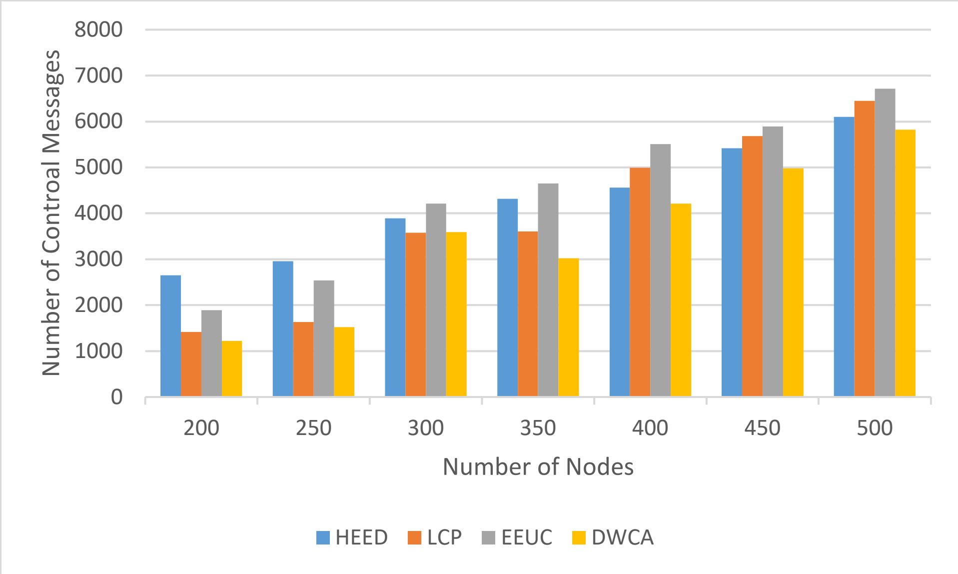

Figure 26: Comparison for Number of Control messages between DWCA, HEED, LCP and EEU

In Figure 27, a comparison between DWCA and HEED, LCP and EEUC in the network of 200 nodes is made in order to evaluate the ***Energy Consumption*** in this scenario. It's clear from the figure the DWCA protocol is more energy-efficient than its counterpart protocols. It is evident that the DWCA network performance is more stable and gradually slopes down when the rounds increase, whereas the other protocols are losing the more nodes when the rounds increase. In terms of network lifetime, the DWCA has extended the network lifetime by 5.3% compared with LCP, HEED 21.5%, and 43.6% with EEUC. The result indicated that DWCA outperforms the most efficient protocol of the other protocols by 5.3%. The results reveal that the HEED and LCP are less capable in such scenario as all their nodes died at around 1300 rounds, and the nodes in LCP died almost in 1500 rounds, whereas DWCA nodes died in 1580 rounds. Hence, DWCA protocol improves network lifetime by around 80 rounds. The justification of this improvement was due to the proposed technique of clustering the network explained previously in this chapter in section 4.4.

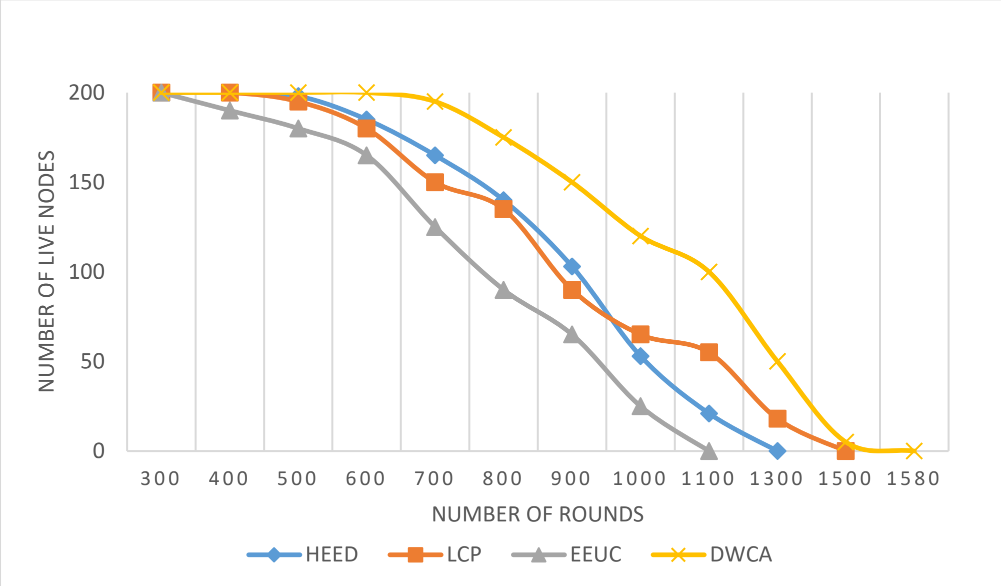

Figure 27: Comparison for the 200 nodes Network Lifetime between DWCA, HEED, LCP and EEU

As stated earlier in section 4.5.4 of this chapter, in the most cluster-based algorithm the network lifetime can be determined by the lifespan of a sensor node in the network; therefore the lifetime metric for sensor network have been investigated by examining the FND, HND and LND. Figure 28 depicts five different network sizes ranging from 200 nodes up to 500, which were used to evaluate the scalability and robustness of the algorithms. From figure 28, it can be noted that DWCA performs better in term of FND with 200 nodes. FND in 200 nodes is significantly improved compared with HEED, EEUC and LCP. However, the DWCA still perform much better in 250, 300 and 350. Nonetheless, in 400, 450 and 500, there is a slight difference in term of the performance for all the protocols. That can be justified by the size of the deployment area that was considered for this experiment. As can be observed from figure 28, the network with 450 nodes the EEUC performed better than all the other protocols, because the formation process in EEUC requires more time than the other protocols, the reason for which can be proved in the next experiments.

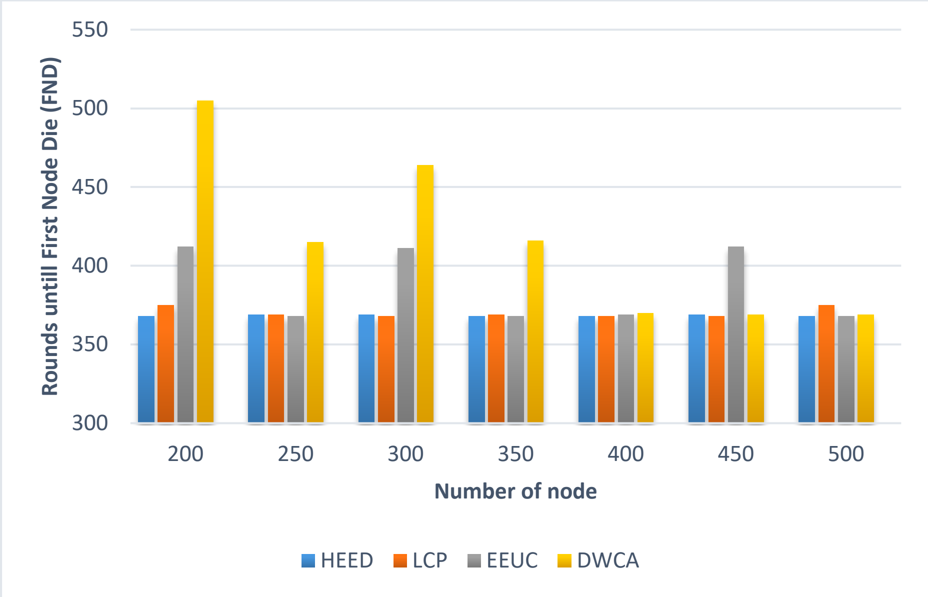

Figure 28: Comparison for FND in different network size between DWCA, HEED, LCP and EEU

In term of HND, figure 29 demonstrates the substantial improvement that has been obtained by the proposed approach, where it is clear in the network of 400, 450 and 500 nodes the half of the nodes in DWCA are almost at 1550, which is nearly double the number for all the other protocols. This achievement has proven that the selection of CHs in DWCA is an efficient mechanism in term of energy consumption.

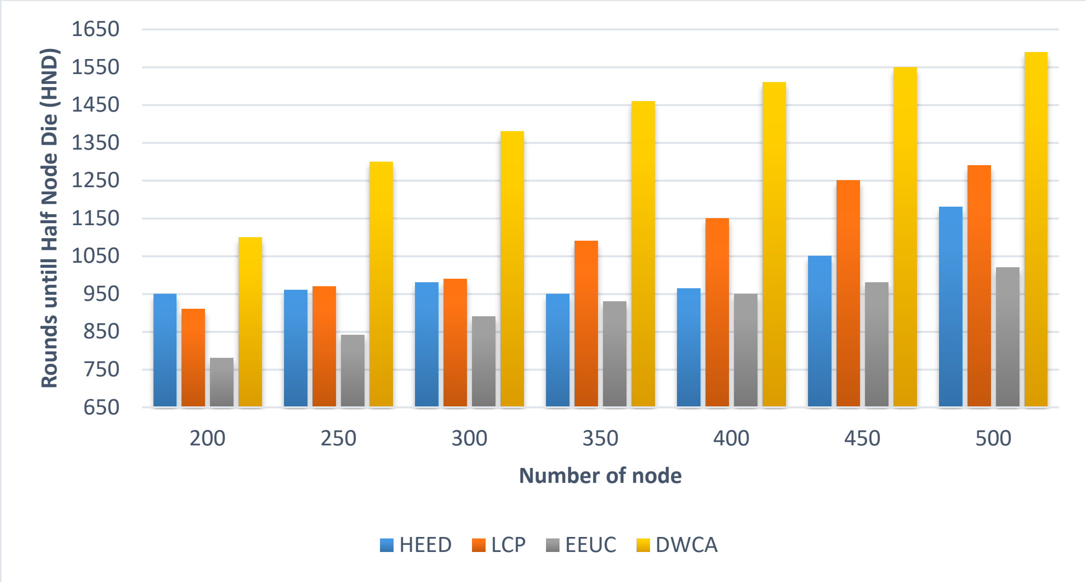

Figure 29: Comparison for HND in different network size between DWCA, HEED, LCP and EEU

Lastly, this part of the experiments is concluded by examining the LND. Figure 30 reveals that the DWCA protocol is energy efficient in all the sets of nodes. It is apparent that the DWCA has improved the total lifetime and the scalability of the network in all scenarios.

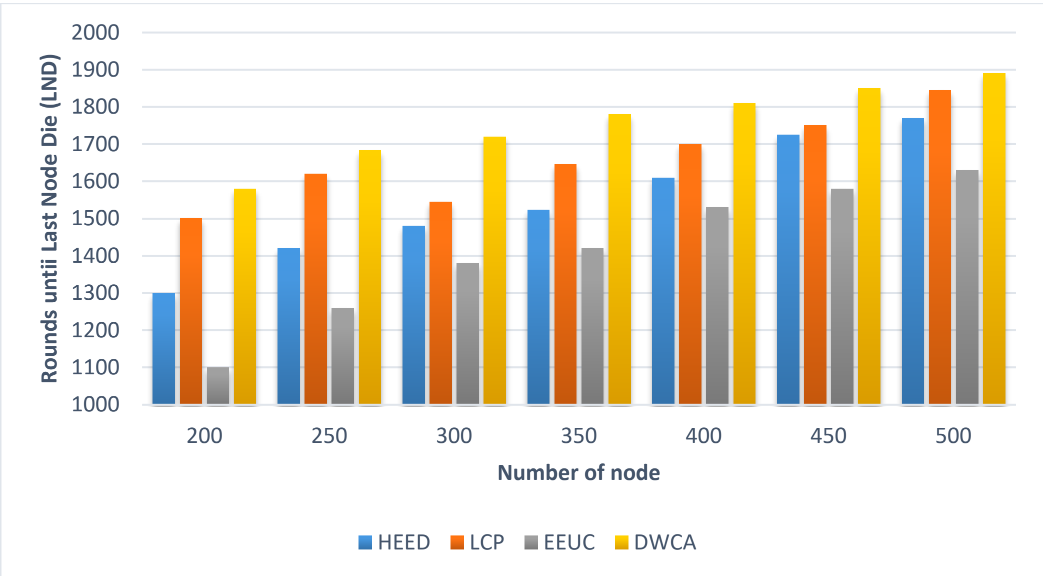

Figure 30: Comparison for LND in different network size between DWCA, HEED, LCP and EEU

In order to ensure the reliability of data delivery to the BS in DWCA, the *Delivered Data Messages* metric is investigated. It can easily be observed in figure 31 the rate of delivered messages by *DWCA* is higher than counterpart protocols in these experiments.

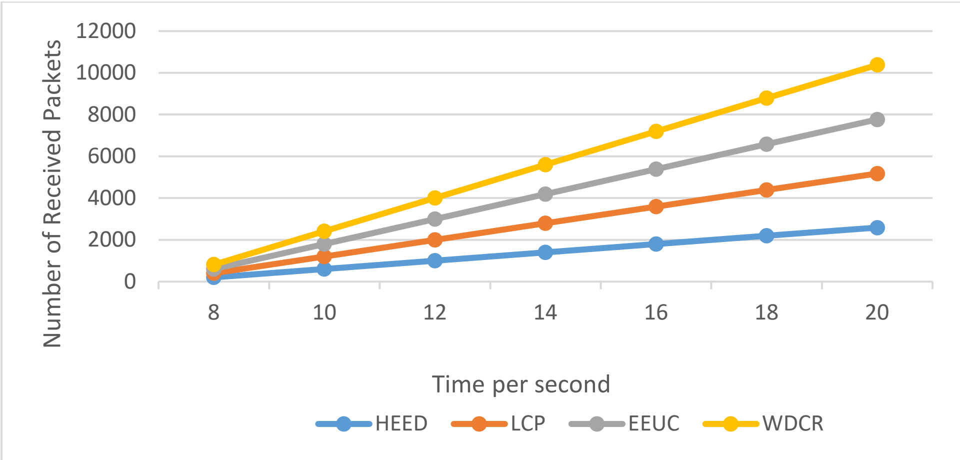

Figure 31: Measuring the number of Packets received by BS between DWCA, HEED, LCP and EEU

4.7 Conclusion

This chapter presented the first contribution of this research, which elaborates the critical issues of clustering mechanism in WSNs. It introduces a new energy-efficient clustering algorithm, DWCA for WSNs, which aims to reduce the overall energy consumption, balance the energy consumption among all nodes and improve the scalability of the network. The results show that DWCA outperforms its counterparts. The method used in DWCA is different from existing works, where a lightweight and critical metrics used for selecting the CHs nodes, which proved the reduction in energy consumption and offered better load balancing. This mechanism can be applied in different applications concerning system parameters. The future work of DWCA is to investigate the multi-hop manner and examine the proposed DWCA under different operating communication patterns such as broadcast and multicast.

Chapter 5

A New Weight based Rotating Clustering Scheme for Wireless Sensor Networks

The previous chapter outlined a new DWCA algorithm, which is scalable and significantly extends the network lifetime. This chapter proposes a new energy weight-based clustering scheme for WSNs. This addresses the load-balancing issue in cluster-based routing protocols.

5.1 Introduction

The research community in WSNs has endorsed Cluster-based mechanisms due to a variety of benefits provided to the sensor-based applications [94]. However, despite a number of research activities associated with clustering in WSNs, some aspects of clustering have not yet been adequately investigated [110] [111]. Minimising overall energy consumption is a crucial requirement when planning WSNs deployment. In general, cluster-based can be defined as small disjointed groups that are formed and managed by a core node, called the Cluster Head (CH). This CH is elected to administer the Cluster Members (CMs) and aggregate their data to forward it directly or indirectly to the Base Station (BS). Dividing a network into clusters provides multiple advantages, such as reducing the routing table size stored in each node [22], conserving the communication bandwidth by avoiding the exchange of redundant messages [21], and isolating routing changes from one cluster to another [131].

Traditional clustering algorithms are based on electing a CH based on the nodes' ID, or their location information when frequent control broadcasting messages are used [58].

Despite these advantages, many factors affect the efficacy of clustering methods, such as electing suitable nodes for the CH role, maintaining and avoiding re-clustering of the created clusters, minimising the overheads of inter-cluster and intra-cluster communication, and prolonging network lifetimes [17][132]. The protocols proposed to address the above issues are not subject to these limitations. In particular, they are not adversely influenced by aspects of the nodes' characteristics, such as battery life, node location and transmission range. In order to prolong a network's lifetime during the scaling of network size, this research proposes the introduction of a novel energy-efficient protocol, named "Weight and Energy-Efficient Rotating Clustering Protocol for WSNs" (*WRCS*) [133].

5.2 Proposed Approach

The proposed *WRCS* aims to elect the most suitable nodes to become CHs while enhancing the overall network lifetime. In *WRCS*, the election process of CHs is mainly based on the node's weight. The weight of each node is determined using a combination of metrics, including the average number of neighbours (*degree* d_i), remaining energy (E_i) and transmission quality (*TQ*). Once the weight is calculated, each node will broadcast a weight packet (*w-pkt*) to its neighbours. Thereafter, the nodes in the network perform a weight comparison to select those nodes with the highest weight in the network. If the node's weight is among the highest, it will become a *CH candidate*. All CH candidates will broadcast (*CH candidate-pkt*) packets that contain a node's *ID* and the Centrality of the Node metrics *CN*. The nodes that do not qualify for CH candidacy enter the sleep mode. The main aim of this process is to select a sub-group of nodes as CH candidates, preventing others from competing to conserve their energy. In the following section, general steps are described by determining how the node weights are calculated.

Step 1: Neighbours Discovery

All nodes in the network broadcast a *HELLO* packet that includes node *ID* and remaining energy E_i. The number of neighbours d_i is determined by equation 9:

$$d_v = |N[V]| = \sum_{V' \in V,\ v' \neq v} \{distance\ (V, V') \ \leq R_t\} \qquad 9$$

where d_v is the number of neighbours within its distance and within its transmission range R_v.

Step 2: Node degree

The degree ND_i of the node is used to calculate the average number of neighbouring nodes of node *i*. Equation 10 determines the average degree d_i for each node:

$$ND_i = \frac{d_i}{Total_n} \qquad (10)$$

where d_i is the number of neighbours of node *i* within its distance, $Total_n$ is the total nodes in the network.

Step 3: Transmission Quality

Transmission quality is measured to determine the connection quality between the BS and the node. Equation 11 is used:

$$TQ = \frac{BS_d}{T_v} \qquad (11)$$

where *TQ* is the node's Transmission Quality, and BS_d is the distance to the BS of the nodes.

Step 4: Remaining Energy

The remaining energy of node E_i is calculated, and the node with the highest energy level among its neighbours have a higher chance to become the CH. The residual energy E_i is calculated using equation 12:

$$E_i = \frac{Ren_i}{Max_{en}} \tag{12}$$

where Ren_i is the remaining energy of the node, and Max_{en} is maximum remaining energy among all the neighbours of node i.

Step 5: Node Weight

Each node in the network will employ the above criteria to define its weight. The weight is calculated using equation 13:

$$w_i = w_1 \times ND_v + w_2 \times TQ + w_3 \times E_i \tag{13}$$

w_1, w_2 *and* w_3, are the weight coefficients that correspond to the system criteria so that the sum of $w_1 + w_2 + w_3 = 1$. The coefficient values considered in this simulation are 0.2, 0.3 and 0.5 for w_1, w_2 and w_3, respectively. In this simulation experiments, the represented values determined by the assumption that the value of the energy is the most important factor in our evaluation.

Step 6: Cluster Head Candidates

Once the weight of each node is calculated, the nodes of the highest weight will be selected as CH candidates. This step aims to select a set of highest weight nodes to compete for final CHs and remove low weight nodes from the competition process in order to preserve their energy.

5.3 Implementation Procedures

In the *WRCS* algorithm, the procedures to form the clusters consist of main two phases, the setup and the steady-state phases. The setup phase is further divided into four more sub-phases: (1) initialisation phase (2) candidate phase (3) finalisation phase (4) rotation phase. The following subsections describe these proposed phases in more detail.

- **Initialisation phase**

All the nodes in the network will broadcast a *HELLO* message across the network to compute how many neighbours it has and calculate their positions. A node then broadcasts its weight back along with the network using a single packet. The pseudocode below represents the initialisation stage of *WRCS.*

Algorithm 1 Initialisation:

```
procedure CALCULATE NODES WEIGHT
    for each node n ∈ N  do
        w1 ← Find Node degree
        w2 ← Find Transmission Quality
        w3 ← Find Remaining Energy
        W=w1+w2+w3
        Broadcast packet (n_ID, W)
    end for
end procedure
```

- **The election phase**

Once all the nodes have broadcast their *weight* to their neighbouring nodes, each node performs a comparison with its own *weight*. The node with the highest weight declares itself a *CH candidate*. The number of *CH candidates* depends on the size of the network. A threshold is defined to control the number of candidates competing for the final CH stage. The 20 highest weight nodes will be selected to compete for final CH positions in a network of 100 nodes. The main intention behind determining this threshold is to elicit all the nodes required to compete as final CHs. All the CH candidates will broadcast a *compete-pkt*. The *compete-pkt* will contain *node ID*, R_{comp} and node degree *centrality DC*. the R_{comp} function of Chengfa Li [96] is used with some changes in the represented values of the d_{max} and d_{min} to the base station values. The R_{comp} is calculated according to equation 14.

$$S_i . R_{comp} = \left(1 - c\ \frac{d_{max} - d\,(S_i, BS)}{d_{max} - d_{\min}}\right) R^0_{comp} \qquad (14)$$

where d_{max}, d_{min} represents the maximum and minimum distance to the base station, $d\ (s_i,\ BS)$ denotes the distance between s_i and the BS, R_{comp} the maximum value of the cluster radius, and c is the constant coefficient between (0- 1). The Degree *Centrality (DC)* of the node *(v)* is determined as in equation 15.

$$DC = \frac{d_v}{n-1} \qquad (15)$$

where d_v is the degree of the node and n is the total number of the nodes in the network. The value of *DC* ranges between 0 and 1, where 0 represent the lowest possible centrality and 1 the highest possible centrality. The following table (2) demonstrates an example of centrality values for a set of 100 nodes in a network when applying equation 15. It's evident that node 3 has the highest centrality value. In the proposed algorithm, if nodes 1, 2, 3 and 4 are CH candidates, node 3 will become the final CH. Table 2 depicts an example of Degree Centrality when compared with Freeman's formula.

Table 2: Prove based on Freeman formula for degree centrality

Node	Degree /n-1	Centrality
1	5/99	0.051
2	8/99	0.081
3	12/99	0.121
4	7/99	0.071

Freeman's general formula for degree centrality for UCINET Software for Social Network Analysis (SNA) [134] is used, as represented in equation 16, to prove the accuracy of the new formula by measuring the degree centrality of the nodes 1, 2, 3 and 4. The outputs are 0.051, 0.081, 0.121 and 0.071 respectively.

$$C_D = \frac{\sum_{i=1}^{g}[C_D(n^*) - C_D(i)]}{[(N-1)(N-2)]} \quad (16)$$

where *CD (n*)* is the degree of the node, *N* is the total number of nodes in the network. The following pseudocode represents the candidate stage of *WRCS*.

Algorithm 2 Cluster Head candidate election

```
1:  procedure SELECT CH CANDIDATES
2:      for each node n ∈ N do
3:          if w_i > w_j & n_i within Threshold then
4:              CH candidate = TRUE
5:              BroadcastCOMPETE − MSG(n_ID)
6:          else
7:              SLEEP MODE=TRUE
8:          end if
9:          On receiving COMPETE-MSG
10:         if (d(n_i, n_j) < n_j.R_comp OR d(n_i, n_j) < n_i.R_comp) then
11:             Add s_j to s_i.CHcompetitors
12:         end if
13:     end for
14: end procedure
```

- **Finalisation Stage**

Once the nodes receive the complete packet (*compete-pkt*) from the other CH candidates, each node will use the R_{comp} function (as described in line 10 of algorithm 2) to check its diameter in comparison to the other candidates. If there are no other candidates, the node will become the final CH; otherwise, the node with the greatest degree centrality will become the final CH, and the other nodes will stop competing, even if they share the same diameter. The below pseudocode represents the candidate stage of *WRCS*.

Algorithm 3 Final Cluster Head election

```
procedure SELECT FINAL CH
    while CHcand = TRUE & CHcompetitors! = 0 do
        if Centrality_i > Centrality_j then
            IsCH =TRUE
            Broadcast CLUSTER HEAD-MSG (n_ID)
        else
            CHcand = FALSE
            EXIT
        end if
    end while
end procedure
```

- **Rotation Stage**

The rotation mechanism of the CH inside each cluster is used to mitigate substantial procedures and create clusters during the set-up phase. Once the clusters have been created in the first round, the rotation of the next CH will take place inside each cluster by selecting the node with the highest weight from among the cluster members. If the energy of the current CH has drained below the threshold. The threshold would then be defined during this stage, as shown in equation 17.

$$T_{CH} = \frac{\sum E_{Residual}}{\sum N} - 1 \qquad (17)$$

where $E_{Residual}$ is the sum of the residual energy in the cluster and n is the sum of nodes in the cluster. The CH will then notify its member to trigger a further election. The node with the highest weight will be declared the next CH until all the nodes have been drained of most of their energy. In this case, the BS will then be notified to re-cluster the entire network. The below pseudocode represents the rotation stage of *WRCS*.

Algorithm 4 Rotate phase

```
1: procedure SELECT CH NEXT ROUND
2:     Nodes Wait for interval of time
3:     if (n_j En < T_CH) then
4:         Broadcast Re-cluster message
5:     else
6:         Select Next node as CH
7:         Broadcast Final CH message
8:     end if
9: end procedure
```

5.4 Experiments and Results

Simulation experiments have been conducted to examine the performance of the proposed *WRCS* [133] when compared with HEED [74], LCP [119] and EEUC [96]. The efficiency of network energy consumption is used as the primary performance parameter, using the Castalia simulator to implement and conduct the performance evaluation.

In the previous chapter, the most important and relevant metrics for measuring energy consumption are the setup messages overhead, total energy consumption, and the network lifetime. In this proposed algorithm, the same metrics are applied to evaluate the energy performance of the network under this scheme. Thus, the performance of *WRCS* against HEED, EEUC and LCP are compared. (1) The proposed algorithm is evaluated by calculating the control messages overhead incurred by various numbers of nodes. (2) The total energy consumption is calculated. (3) The network lifetime is measured via three different metrics: FND, HND, and LND. Finally, the outcome of the data messages delivered to the BS was observed.

The following assumptions considered for evaluating *WRCS* against the most well-known clustering algorithm:

- Each node has limited energy and equal initial energy.
- Each node is capable of exchanging messages with other nodes in its transmission range.
- The network topology is static throughout the network lifetime.
- The BS is located away from the deployment field.
- All of the nodes are homogeneous.
- The distance between the node and the base station is measured based on the strength of the received signal.
- The maximum number of hops each node is capable of supporting under the experiment's assumption is two. Table 3 shows the parameters and provides the values for simulation experiments.

Table 3: Simulation Parameters and Values for WRCS, EEUC, HEED and LCP

Parameter	Value
Deployment Domain	250 m x 250 m
Deployment Method	Uniform, Random
Simulation Time per second	500–1100 seconds
Sensor network number of nodes	200, 250, 300, 350, 400, 450, 500
Initial energy	25 Joules
Node Status	Sationary
Application ID	Throughput test
Base Sation location	(275, 125)
Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	WRCS, EEUC, HEED, LCP

First, (*setup messages overhead*) which indicates the relationship between the average number of control packets and the number of nodes in different network sizes have been investigated. Several simulation experiments carried out according to table 3. The nodes deployed in throughput application network are ranging from 100 to 500 nodes randomly deployed in the area of 250m x 250m, the position of the BS is 275, 125 away from the sensing domain between LCP, HEED, EEUC and WRCS. Figure 32 shows the average number of messages involved in forming clusters obtained from Castalia Simulation, and the presented result demonstrates the comparison of proposed WRCS and HEED, LCP and EEUC. As shown, the WRCS achieves fewer control packets compared with LCP, HEED, EEUC protocols. In comparison to the HEED, the average number of control packets decreased by 71% in the 100-node model and 60% in the 500 nodes network.

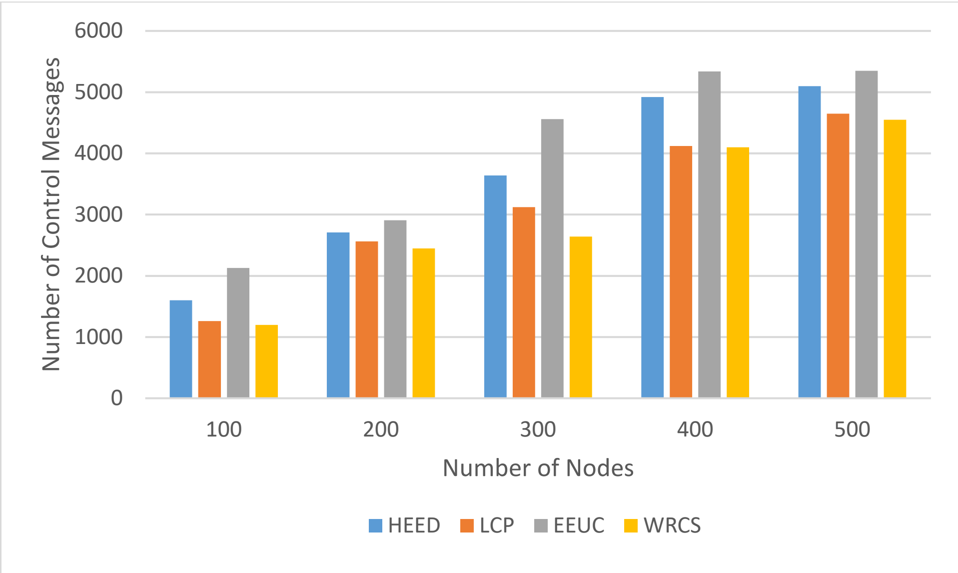

Figure 32: Comparison for Control Messages in different network size between WRCS, HEED, LCP and EEU

Figure 33 represents a comparison between four protocols and the total lifetime in a network of 100 nodes. It is apparent that WRCS outperforms the most efficient (*Energy Consumption*) protocol by 10%. This result demonstrates that the EEUC is less efficient in terms of energy conservation, as all its nodes die rapidly when compared to other protocols. Both HEED and LCP perform better than EEUC, but their nodes died before those of the WRCS protocol. The findings demonstrate that the nodes of the EEUC did not remain live after 650 rounds. The LCP completed 850 rounds, and all the nodes in HEED died within 900, whereas WRCS lost all its nodes after 950 rounds. Hence, the *WRCS* protocol improves the network lifetime by approximately 50 rounds. It's believed that the two factors account for prolonged network lifetime under *WRCS*: considering multi parameters to elect the CH and selecting a set of the highest weight nodes to compete for the final CH and using a rotation technique inside each cluster.

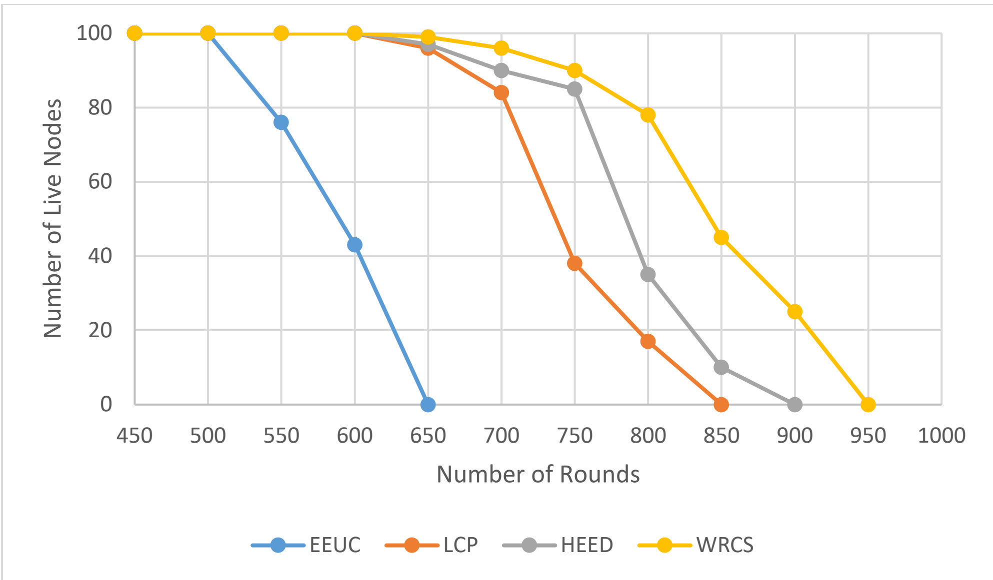

Figure 33: Network Lifetime Comparison for 100 nodes Network between WRCS, HEED, LCP and EEU

As introduced in chapter 3, the objectives of cluster-based are feasible for WSNs, and most importantly, the applied algorithm for routing data must take into account sensor nodes limited energy. Consequently, to ensure that the proposed mechanism can be applied for different size networks, the (*Network Lifetime*) have been examined for all the protocols presented in table 4. The network lifetime metrics are presented in chapter 4, section 4.5.3. Figure 34 represents the FND metric simulation results in a comparison between WRCS and its counterpart protocols in a network size ranging from 100 to 500 nodes. The figure (34) confirms the effectiveness of the WRCS algorithm in term of (*FND*), where the WRCS performs better in all network sets. In WRCS, with 100 nodes network, FND is the most effective compared to the other sets, whereas it decreases in 200, 300 and 400 sets at approximately the same level, in the 500 nodes network, it decreased farther than in the others. The results show that WRCS lasts longer than the other protocol in term of FND in all networks sets. In comparison with the best performance of the other three protocols in the networks, WRCS is more efficient than EEUC in the 400 nodes network by 21.7% and more efficient than the LCP and HEED in the 100 nodes network by 16.6% and 7.5% respectively.

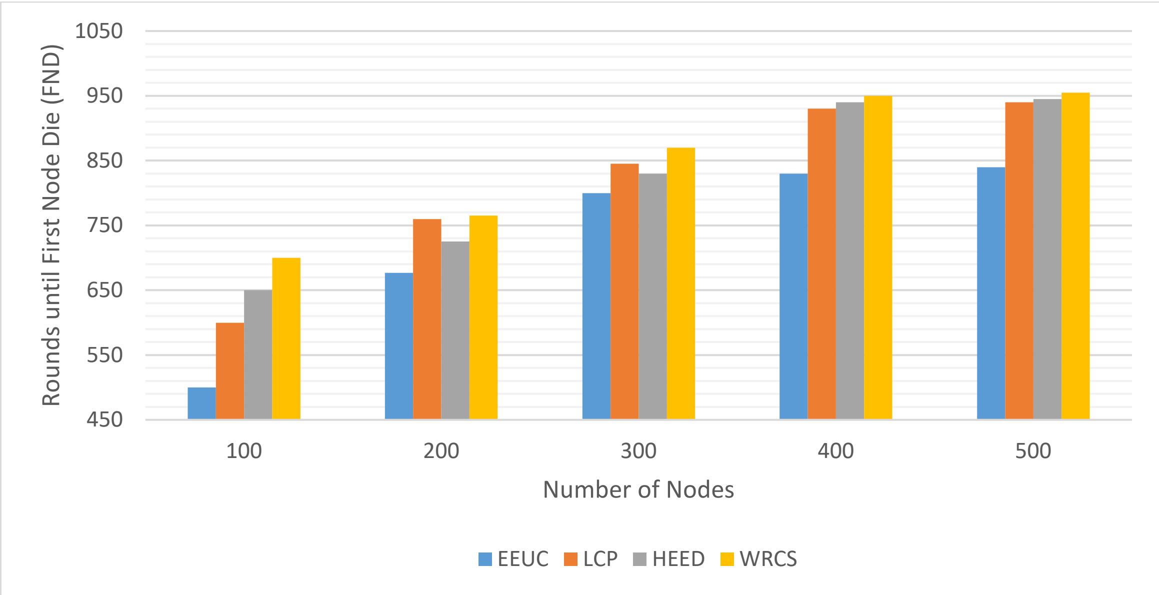

Figure 34: Comparison for FND in different network size between WECS, HEED, LCP and EEU

Figure 35 shows the HND for the four protocols across different scales of networks. As can be seen, the WRCS performs better than other protocols, reaching a maximum of 894 rounds in the 400 nodes network. In comparison to the best performance of the other three protocols, WRCS is more efficient than EEUC in the 300 nodes network by 38.7% and more efficient than the LCP and HEED in the 300 nodes network by 14.6% and 8%, respectively.

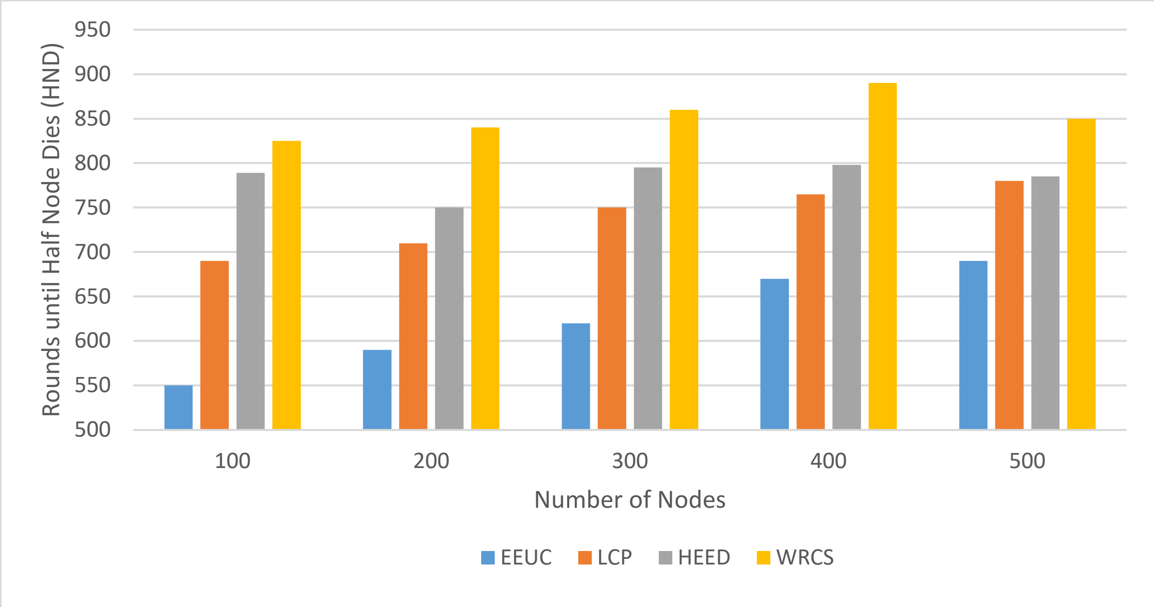

Figure 35: Comparison for HND in different network size between WECS, HEED, LCP and EEU

Figure 36 illustrates the (LND) metric across the four protocols tested by different network size, ranging from 100 to 500 nodes. According to the results, the WRCS performs better than the other protocols in all network sizes. In WRCS, the 400 and 500 node networks perform the best under LND, at 1200 and 1150 rounds, wherein 100 and 200 node networks it decreases to just over 950 rounds. In comparison to the other three protocols, in their best performance network, WRCS is more efficient than EEUC in the 500 nodes network by 38% and more efficient than the LCP and HEED in the 400 nodes network by 70% and 61.4% respectively.

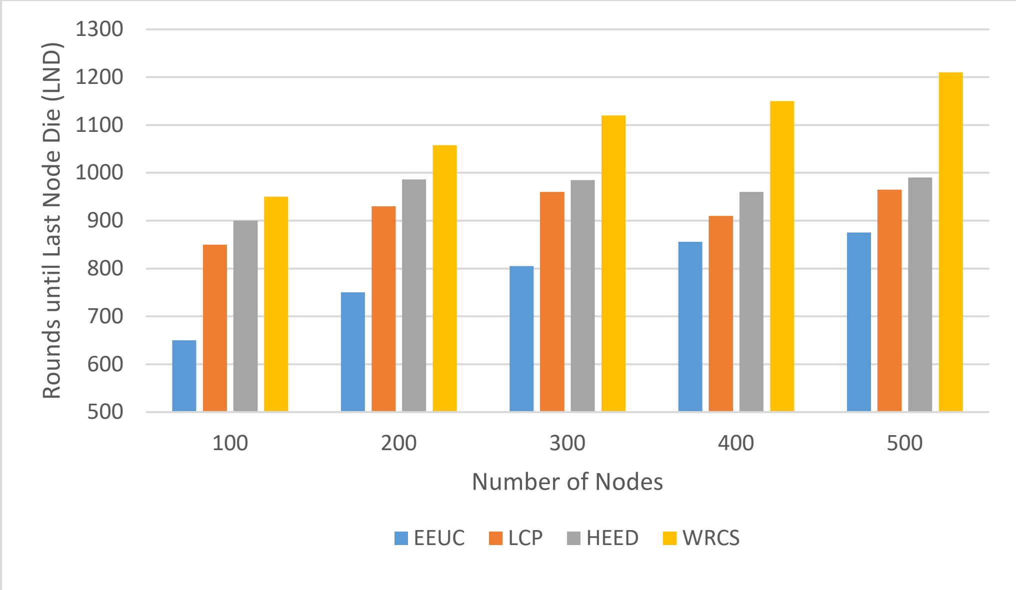

Figure 36: Comparison for LND in different network size between WECS, HEED, LCP and EEU

Figure 37 provides a comparison of *Average Data Message Received* by BS from CHs nodes in one round. The conduct, simulation experiments depicted in figure 37 represent the data received by the BS, where the round time is 20 seconds. The obtained results reveal the efficiency of WRCS in terms of data delivery rate and stable performance over relevant protocols. However, for the EEUC, which had worst energy-efficiency in previous experiments, the data delivery rate of EEUC in one round is higher than HEED and LCP, which can be justified by the persistent messages sent to the BS during the set-up phase.

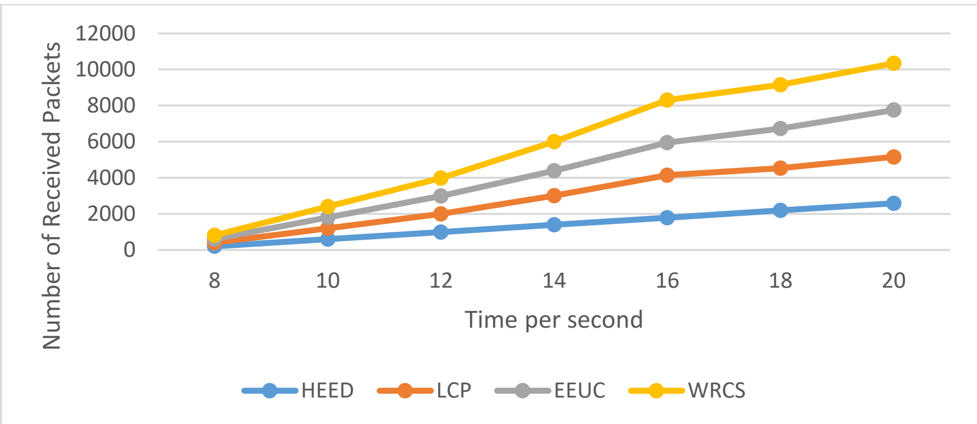

Figure 37: Measuring the number of Packets received by BS between WRCS, HEED, LCP and EEU

5.5 Conclusion

This chapter introduced a new energy-efficient cluster-based scheme for WSNs. In the proposed scheme, key metrics have been adopted in order to guarantee the best selection of optimal nodes for the CH role. These effective metrics, which include the remaining energy, transmission range, the number of neighbouring nodes, and the degree centrality, are the most appropriate according to the obtained simulation results. The new dynamic procedures used to select CH candidates before deciding which nodes will become the final CH and the eliminated frequent re-clustering process are the key contributions in WRCS, which provided the best network performance and extending network lifetime. Another reason for the exceptional performance of WRCS is the role for degree centrality metric, where the CHs in the first rounds have to be in the centre of the cluster, which balanced energy consumption by reducing the transmission power of the nodes within the cluster. The results obtained, based on comparing lifetime and data delivery rate, show that the WRCS algorithm consistently outperforms its counterparts in terms of these metrics and scalability. Compared with EEUC, LCP and HEED in their best performance network in term of network lifetime, the WRCS is more efficient by 38% than EEUC in 500 nodes network and more efficient by 70.5% and 61% than the LCP in 400 nodes respectively. The proposed mechanism can be extended for further scenarios testing such as mobility scenarios.

Chapter 6

Reliable and Energy-Efficient Two-Level Unequal Clustering Mechanism for WSNs

6.1 Introduction

In Wireless Sensor Networks, clustering sensor nodes into disjointed groups are common and are used to achieve load balance and increase the lifetime of a network [135]. In particular, traditional unequal clustering mechanisms [78], where small clusters are located close to the base station, suffer from rapid energy depletion due to heavy traffic load by inter/intra-cluster communication. To overcome the problem of the traffic load on the clusters near the base station, this research proposes a new Two-Level, Unequal Cluster, Lightweight mechanism (REUCS) [136], based on a threshold defined by the BS and using the node's residual energy and the distance from BS. Moreover, a new re-clustering technique has been developed where CHs rotate locally in each cluster on a per-level basis.

The fundamental motivation for this study is to enhance network lifetime, to achieve scalability and reliable node communication, whilst considering the node's resources and the nature of the random deployment. The construction of clusters in randomly deployed nodes can be challenging, especially when applying a distributed algorithm [22]. The load on selected CHs in each round is burdened by managing intra/inter-cluster communication. Therefore, CHs deplete their energy more than CMs, and they cannot send their data until a new clustering process starts [22]. This problem is worse when applying a periodic selection of CHs, as in [62], where fewer energy nodes are available to be selected to become the CH. Other algorithms use node residual energy as the prime criteria for nodes to become CH [74]; this mechanism is effective for mitigating the issue of selecting fewer energetic nodes as CH in certain applications. In large-scale clustered networks, it is efficient to employ multi-hop communication between CHs to transmit gathered data to the BS and overcome signal propagation problems [137]. Nevertheless, the issue near the BS clusters persists, due to incoming traffic load from far away clusters. This issue results in the near BS CHs potentially depletes their energy much earlier [78]. The loss of these critical CHs will significantly affect the performance of the network and could isolate the BS.

6.1.1 First Motivation: Cluster formation process issue.

The facts, as mentioned earlier, influence the process of selecting suitable nodes to become CH during the set-up phases. Several criteria for selecting optimal nodes to become CHs have been studied in the literature [96][138][139][140]. However, most of these algorithms apply a periodic selection or are based on various parameters, where the messages that are exchanged to gather another node's information, affect the network lifetime.

- **First Contribution**: different techniques proposed in the literature for selecting CHs among randomly deployed nodes were reviewed and concluded the review by developing a novel lightweight selection of CHs in the first round and reducing the set-up phases to construct clusters, as shown figure 38, (A) for the proposed mechanism, compared with (B) for traditional clustering algorithms. This has been achieved by eliminating the neighbour discovery process and gathering another node's information.

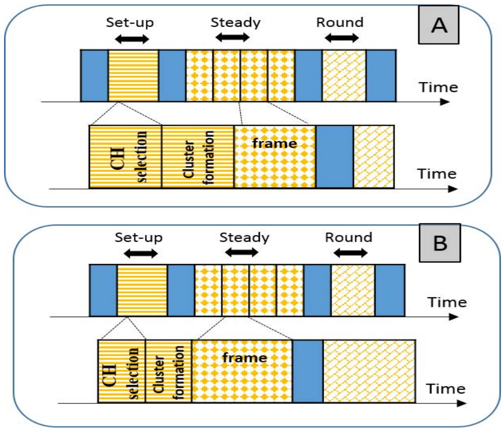

Figure 38: Packet difference Between Traditional Clustering Algorithms and REUCS

6.1.2 Second Motivation: Re-clustering process.

The vital objective of clustering is to maximise network lifetime, stabilising network topology, data aggregation and scalability [57]. The conflict between the energy consumption and frequent re-clustering of the entire network results in excessive energy waste; this is mainly caused by control messages exchanged to re-cluster the network in each round [141][142][143].

Second Contribution: re-clustering scheme within levels, proposed to stabilise network topology and conserve network energy. Frequent re-clustering or other re-clustering schemes (explained in chapter 3) are inefficient when compared with REUCS. The re-clustering of the entire network in each round, or when one of the clusters depletes their energy, is not sufficient because of the extensive overhead and re-clustering process [142]. In REUCS, local CH rotation inside the cluster was applied, based on the energy threshold, and when the entire cluster reached the defined threshold, the BS triggered a new clustering process for that level alone.

6.2 Proposed Approach

- **REUCS Basic Idea**

The proposed algorithm operates on the basis of rounds, as in most WSN clustering algorithms. Once the nodes are deployed randomly, the BS broadcasts a single packet to the nodes. Upon receiving the BS-packet, the nodes will determine their approximate distance from the BS based on the received RSSI. The clustering process comprises of two phases: the set-up phase and the steady phase. During the set-up phase, the number of nodes selected to be CHs and the non-CH nodes joins the closest CH based on the strongest received signal. The steady phase inter/intra data transmission in the network then takes place. In contrast to the counterpart algorithms, in the REUCS's initial set-up phase, neighbouring node information is not required in order to select a CH. The decision to select nodes as CHs is based on effective utilisation of local node information: residual energy and the distance from the BS. REUCS forms two levels of network clusters based on the threshold identified by the BS.

- **Network structure**

In REUCS, the clustering structure has the following assumptions: N heterogeneous sensor nodes randomly deployed in the area of dimension M x M; the BS is located outside the sensing area. n_i nodes are selected as CHs where $n_i \in N$ then C clusters are constructed and $n_i \in C$, the C is defined as $C = (C1,\ C2,\ ....\ C_k)$. Then route data packet through associated CH. The CH aggregate and process the member data before forwarding it as a single packet to the next-hop CH or to the BS (in case it is within the defined first level if the multi-hope condition is not satisfied for the first level multi-hop). The following are system assumptions for both the nodes and the BS:

- The nodes have a limited power source, and the base is not energy-constrained.
- The deployed nodes have different initial energy. However, the processing, computational and communication capabilities are similar.
- The nodes are stationary throughout the network lifetime and are deployed randomly in the area of interest to form WSNs.
- Nodes are location unaware.
- Links are symmetric between nodes.
- The BS is based outside the sensing area.
- The nodes can compute the approximate distance to another node by Received Signal Strength Indication RSSI

- **Energy models**

The energy model considered for energy consumption and network lifetime is based on the [96] model. The model uses both free space (d^2 power loss) and multi-path fading (d^4 power loss) for the channel models. Energy consumption is decided dependant on the distance between the transmitter and the receiver. Equation 18 illustrates the energy spent to transmit an *l*-bit packet over distance *d*.

$$E_{Tx}(l,d) = \begin{cases} lE_elec \; + \; l\epsilon_{fs}d^2, & d < d_o \\ lE_elec \; + \; l\epsilon_{mp}d^4, & d \geq d_o \end{cases} \quad (18)$$

The radio expends energy when receiving the message as

$$E_{Rx}(l) = lE_{elec} \quad (19)$$

6.3 Implementation Procedures

- **Base Station operation**

In REUCS, the BS is assumed to know the size of the deployment field and can adjust its transmission levels into two levels: maximum and minimum. Figure 39 illustrates the two transmission levels of the BS, the Tr_{max} in yellow lines and the Tr_{min} in blue squares. Based on that assumption, the BS can set a regional threshold for the nodes to identify which level they belong. In the proposed strategy, the threshold value of the network levels can be calculated by equation 20.

$$threshold = \frac{area_{max} - Tr_{min}}{Tr_{max} - Tr_{min}} \quad (20)$$

where $area_{max}$ is the edge of the network, as shown in figure 39. The BS will broadcast one single control packet containing the BS ID, Level threshold, Tr_{max} , T_{rmin} and other control data.

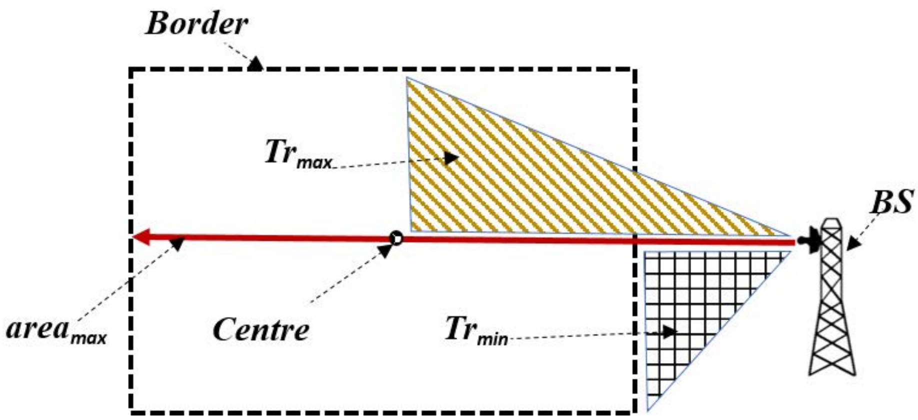

Figure 39: Base Station Level's Threshold Metrics

- **Cluster formation**

The size of the cluster in the network has a significant impact on network lifetime L. Thus; the goal is to form unequal clusters where clusters near the BS level are smaller than are those in the second level. The idea of unequal clusters was derived from EEUC [96], with some modification to implement the new strategy of unequal two-levels clusters. In order to achieve the new strategic goal, the nodes first determine the level to which they belong when they receive the BS control packet. Upon receiving the BS control packet (which contain *BS ID*, Level threshold, Tr_{max} and Tr_{min}), the nodes can determine the approximate distance from the BS by *RSSI*. Subsequently, all the nodes are required to assess their level n_{level} by employing equation 21.

$$n_{level} = \frac{d(n_i, BS) - N_T r_{max}}{N_T r_{max} - Tr_{min}} \tag{21}$$

where $d(n_i;BS)$ is the distance from the BS and Tr_{min} is BS minimum transmission range, $N_T r_{max}$ is the maximum node transmission, which can be obtained by employing equation 22.

$$N_T r_{max} = d(n_i, BS) - Tr_{min} \tag{22}$$

Figure 40 demonstrates an example of $N_T\, r_{max}$ and Tr_{min}.

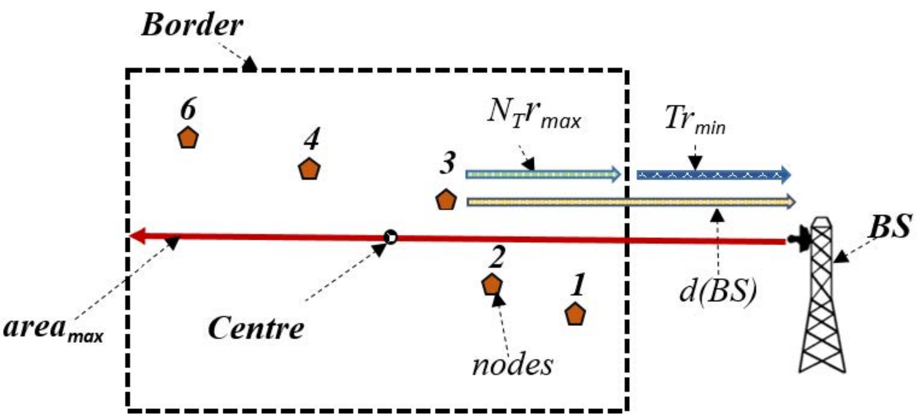

Figure 40: Node's Levels Threshold

Once n_{level} is obtained, the deployed nodes broadcast the cost function (fn_{max}) for CH selection. fn_{max} is a combination of node residual energy E_i and distance from the BS $d(n_i;BS)$. Each node will broadcast the value of $f(E_i + d(n_{i,} BS))$, which can be received only by the nodes within the same n_{level}. In the first round, it's required to ensure the CHs near the BS are selected as the highest energy level in order to sustain incoming traffic; those that are far away will depend on the distance from the BS and the competition radius. The $f_n max$ value for the nodes near the BS will be influenced by the energy level in order to obtain the highest level. Therefore, they will have more chance to become CHs, whereas nodes that are far away from the BS the distance will influence the value of $f_n max$. To ensure the selection of optimal nodes for the role of CH, $f_{\max=}$ $(n_i 1, n_i 2, \ldots\ldots N_i)$ becomes a potential CH in the level. The E_i is calculated as in equation 23

$$E_i = (1 - \frac{E_{res}}{E_{max}})X. \tag{23}$$

where E_{res} is the residual energy of i and E_{max} is the maximum energy of i, X is a random number between (0 and1), which ensures $E_i \neq E_j$. The $d(n_i;BS)$ is the distance from n_i to BS. The $d(n_i;BS)$ is measured by the power of the received signal strength P_{R_X} which was represented by [144] and illustrated in equation 24.

$$P_{R_x} = P_{T_x}.G_{T_x}.P_{R_x}\frac{\lambda}{4\pi d} \tag{24}$$

where P_{R_X} and d is the distance from the sender. the *RSSI* in equation 25 is the ratio of power received to P_{Ref}

$$RSSI = 10.\log(\frac{P_{r_x}}{P_{Ref}}) \quad (25)$$

In the final stage in constructing the cluster, the nodes in each level compete to become the final CH according to equation 27.

$$nR_{adu} = 1 - g.\frac{N_T r_{max} - d(n_i, BS)}{N_T r_{max} - Tr_{min})} R_d \quad (27)$$

where $NT\,r_{max}$ is the node maximum transmission power, and Tr_{min} is the BS minimum transmission range. g is the constant number from (0,1). Unlike the EEUC algorithm [96], were the d_{max} and d_{min} are pre-defined, in REUCS, the $N_{Tr_{max}}$ and Tr_{min} can be obtained during network configuration.

Figure 41 demonstrates the two-level network design for REUCS. As is evident, the REUCS creates two-level clusters. In level A, clusters are smaller, whereas the reverse is true of level B.

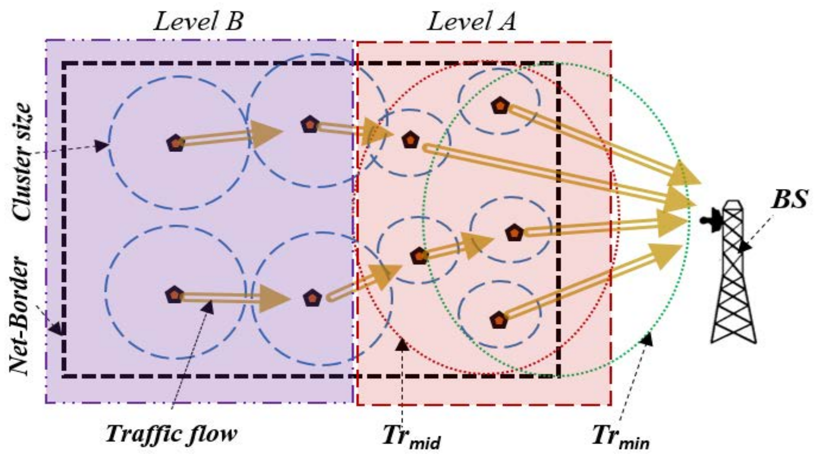

Figure 41: Network structure of REUCS

The following pseudocode summarises the Cluster Formation algorithm.

Algorithm 1 Cluster Formation algorithm

```
procedure BS broadcast
for each n ∈ N do
        n ← d(ni, BS) Computed in equation (5)
        n ← (nlevel) Determine (equation (4)
        n ← fnmax
end for
if nlevel < Threshold then
        ni ← Level1
    costFunctionMsg (fnmax)
else
        nj ← Level2
    costFunctionMsg (fnmax)
end if
    On receiving costFunctionMsg
if nilevel == njlevel then
        Add nj to ni.compteteList
        FinalHeadMsg (ID; (nRdu))
end if
end procedure
```

- **Re-Clustering process**

To avoid the traditional re-clustering for the whole network in a fixed interval (which negatively affects network lifetime), a new mechanism has been developed to allow the nodes to rotate the CH role locally, inside the cluster, until all the nodes have performed the CH role. The local re-clustering is triggered only if the CH's energy falls below the energy threshold.

Once all the cluster nodes have performed the CH role, the last CH sends a re-clustering message and the average energy of the nodes inside the cluster to the BS in order to trigger a new clustering process. Upon receiving the re-clustering message, the BS checks the level in which the re-clustering message came and determines the average energy level in that cluster. If the average energy level in a cluster is not below the threshold, then the BS triggers a new re-clustering process for just that level; otherwise, new network clustering will be triggered. The following pseudocode summaries the local and levels CH rotation algorithm.

Algorithm 2 Local and levels CH rotation algorithm

```
1: procedure CH Broadcast rotate
2:  if n ∈ C_CH then
3:      if Ei_res > E_ClusterMemeber then
4:          n_i = newCH
5:      end if
6: end if
7: if Ei_res < Cluster_Threshold then
8:      BS broadcast level_i re _ cluster
9: end if
10: end procedure
```

6.4 Experiments and Results

This section describes the simulation environment that has been used to assess the performance of the REUCS. The performance of the presented REUCS protocol is evaluated using a Castalia simulator [124] that is built on the OMNeT++ [125] platform and has been previously described in Section 4.4. The network lifetime is examined as the primary performance parameter. The network lifetime is often addressed by three criteria: 1) When First Node Dies (FND); 2) When half the nodes Die (HND); 3) When the last node dies (LND). In order to validate the simulation results, the REUCS results are compared with the EEUC protocol [96], as well as a state of art algorithms such as WDCR [145] and DLCP [146]. Table 4 shows the parameters and values considered for simulation experiments.

Table 4: Simulation Parameters and Values for REUCS, WDCR, EEUC and DLCP

Parameter	Value
Deployment Domain	250 m x 250 m
Deployment method	Uniform, random
Simulation time limit	500–1100 seconds
Sensor network number of nodes	100, 200, 300, 400
Initial energy	25 J
Node Statue	Stationary
Application ID	Throughput test
Base Station location	(275, 125)
Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	REUCS, WDCR, EEUC, DLCP

Figure 42 shows a comparison between REUCS protocols against WDCR, EEUC and DLCP in order to examine the total lifetime in a network of 100 nodes. It can be seen from figure 40 that the newly proposed mechanism outperforms DLCP as the most efficient protocol by 10%. This result demonstrates that the EEUC is less efficient in terms of energy conservation, as all its nodes die rapidly when compared to other protocols. Both WDCR and DLCP perform better than EEUC, but their nodes died before those of the REUCS protocol. The findings demonstrate that the nodes of the EEUC did not remain live after 850 rounds. The DLCP completed 950 rounds, and all the nodes in WDCR died within 900, whereas REUCS lost all its nodes at 1000 rounds. Hence, REUCS improves the network lifetime by approximately 50 rounds. It's believed that two factors account for the prolonged network lifetime under REUCS: considering multi parameters to elect the CH and selecting a set of the highest weight nodes to compete for the final CH and using a rotation technique inside each cluster.

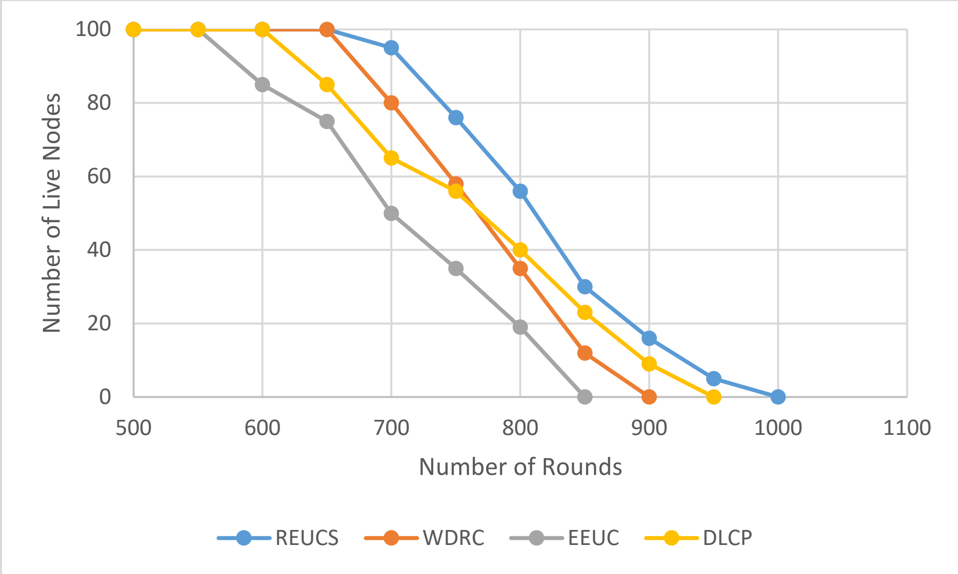

Figure 42: Network Lifetime Comparison for 100 nodes Network between REUCS, WDRC, EEUC and DLCP

Figure 43 shows the rounds until the first node dies (FND) and the number of nodes in the network, which ranges from 100 to 400 nodes. From this figure, it can be noted that FND in REUCS outperforms all algorithms.

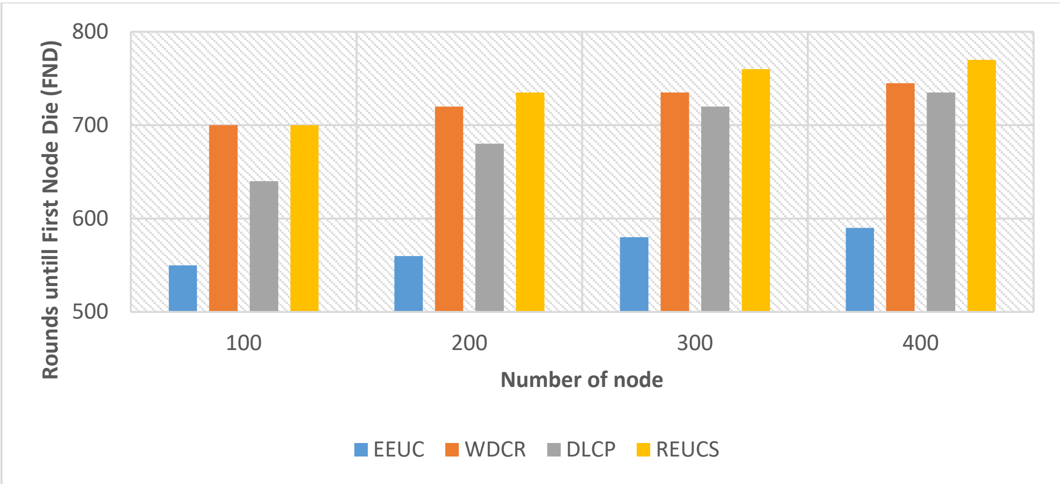

Figure 43: Comparison for FND in different network size between REUCS, WDRC, EEUC and DLCP

Figure 44 shows the HND for the four protocols in different network sizes. As can be observed, the REUCS outperforms WDCR, EEUC and DLCP protocols. In 200 nodes network, the REUCS reaches HND in 830 rounds whereas the EEUC does in almost

745 rounds. In HND, it can be noted that the REUCS and WDCR nodes conserve their energy better than EEUC and DLCP.

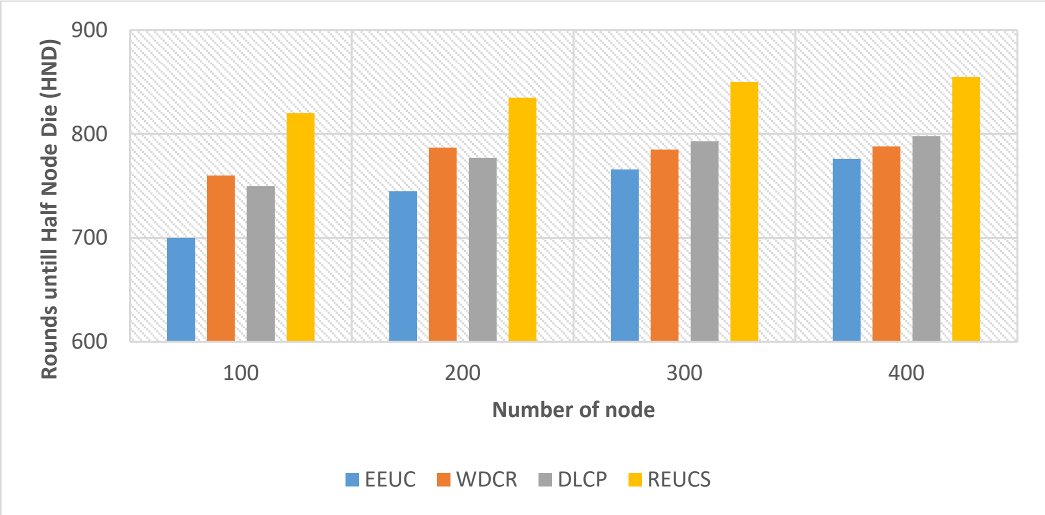

Figure 44: Comparison for HND in different network size between REUCS, WDRC, EEUC and DLCP

Figure 45 shows the rounds until the last node dies (LND) in the four protocols tested by different network size ranging from 100 to 400 nodes. According to the results obtained, the REUCS performs better than the other protocols in all network sizes. In REUCS the 100, 200 and 400 nodes network has the highest performance in LND at 850, 899 and 850 rounds respectively, whereas, in the 300 node networks, it reaches around 830 rounds. In comparison with the other three protocols in their best performance network size, REUCS is more efficient by 19.6% than DLCP in 300 network nodes. And more efficient by 18.5% than WDCR in 200 nodes and 32.2% than the EEUC in 300 nodes respectively.

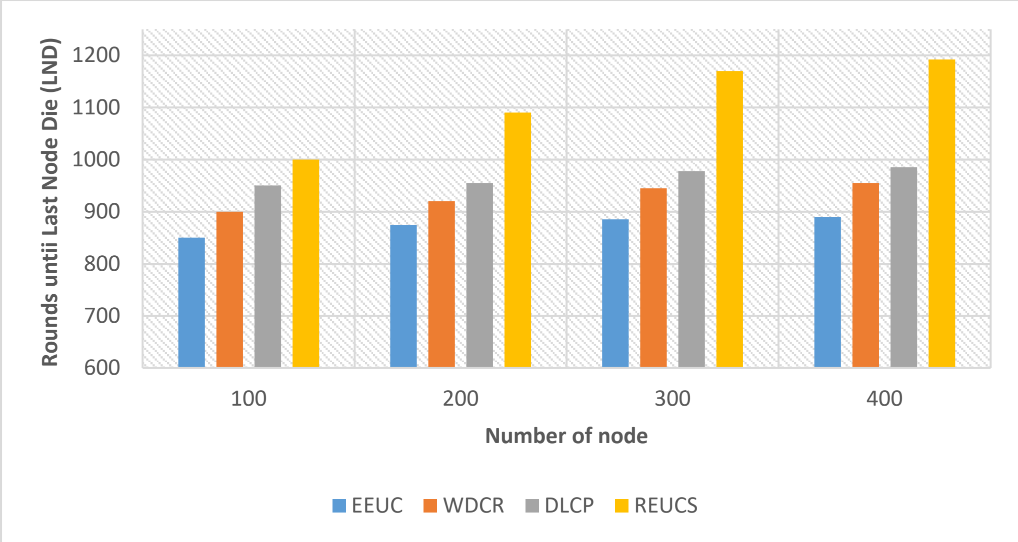

Figure 45: Comparison for LND in different network size between REUCS, WDRC, EEUC and DLCP

6.5 Conclusions

This study proposed a novel clustering mechanism in order to increase network lifetime. Dividing the network into two levels of clusters approved that it can reduce the energy consumption and balance the load among nodes. In REUCS, the selection of cluster heads is based only on two local metrics: node residual energy and distance to the base station. Using only these two metrics helped to reduce overheads in the set-up phase. The frequent re-clustering process in traditional clustering algorithms is eliminated, which has a significant impact on energy consumption. The simulation results show that the REUCS algorithm outperforms its counterparts in terms of network lifetime and scalability.

Chapter 7

Conclusions and Future Directions

This chapter concludes the thesis by outlining the contributions and providing an evaluation of the key results of this research.

7.1 Thesis Summary

Due to the proliferation of new applications, WSNs have played an essential role in the evolution of modern technologies and will continue to play a vital role in the migration toward facilitating future applications for an Internet of Things (IoT). In the last two decades, WSNs have garnered a great deal of interest within the research community. A sensor node has the ability to construct a network autonomously in order to sense events in the physical environment. Moreover, the network can accommodate hundreds or thousands of nodes and communicate via a wireless medium. The miniature sensor node is equipped with a sensing unit, a data processing unit, memory and a small battery that supplies power for the nodes. However, sensor nodes are characterised by many resource constraints concerning energy, processing power, storage and transmission range [26]. These limitations pose many challenges in terms of the network lifetime, reliability, quality of service and scalability [41]. As a result, new algorithms are required that takes these limitations into account to extend the network lifetime.

One of the main objectives of this research is to address the energy consumption problem within the sensor network, which is mainly influenced by many factors, such as the topology structure. This research proposed three mechanisms to fulfil the gaps in the literature and achieve a reliable and scalable network with a longer lifetime.

7.2 Research Findings and Contributions

As outlined in the research aims and objectives outlined in chapter 1, many techniques/ mechanisms associated with energy-efficiency in WSNs have been reviewed and investigated with the view to identify the gaps in the existing literature and present an alternative. While there is considerable scope for energy-efficiency in WSNs, this research is limited by both provided resources and time scale. The following section provides more detail regarding the findings and contributions of this research.

Chapter 4 broaches the issue of probabilistic and single metrics mechanisms to assigning CH nodes within randomly deployed nodes. This process significantly increases node energy consumption. Moreover, as the deployed nodes have different roles in the network, their energy consumption will differ. For instance, CH nodes consume more energy than ordinary nodes in the cluster due to handling network inter/intra communications. Another factor affecting the performance of the network is the location and distance of the nodes from the BS. This research presented a potential solution to these issues and consisted of a new mechanism to managing the cluster-based in WSNs, where the selection of CHs is based on three local parameters: the number of adjacent nodes, residual energy and the node's distance from the BS. These defined parameters can be computed locally by the nodes without any BS or user involvement in the process of constructing the network, which's one of many requirements of WSNs applications to be fully distributed. A new selection method for CH candidates was presented. The process guarantees the selection for suitable CHs that ensure the efficiency of selected nodes. In chapter 4, the procedure of the proposed algorithm was described in which the process of forming the network has two phases: the set-up phase and the steady-state phase. The following section highlights the proposed mechanisms contribution.

In Chapter 5, in many WSNs application, it's required to construct a network that can work unattended by a human, performing all of its tasks autonomously. The proposed mechanisms in chapter 5 take this goal into account, developing a network that is fully distributed and can be deployed in any area at random. In this mechanism, homogenous nodes were considered. These nodes are identical in processing power, energy source and storage capability. Heterogonous nodes can be adopted by this mechanism, where the main criteria for CH selection are based on the weight of the nodes. The proposed mechanism developed a new Degree Centrality metric for the CHs nodes, which was adopted from social networks.

The new technique has proved its efficacy by the simulation result obtained. Moreover, to select the most appropriate nodes and meet the energy-efficiency requirements of the network, the role of CHs in cluster-based mechanisms in WSNs must be considered. Failure to select suitable nodes for the CH role can result in inefficiency of the network. This mechanism focused on ensuring the selection of CHs that are particularly suitable for meeting the WSNs requirements to be effective and provide better network performance. In the proposed mechanism, the node energy level is considered. In that each node is weighted to ensure the selected CHs have enough energy to serve the members at that round and until the new round starts. Once the new round starts, a new node with enough energy selected. It is essential for the node to accurately assess its number of neighbours because this helps to decide how many CH candidates are required in that specific area of the network. In LEACH and HEED, the distance of each node from the BS is not considered, which’s one of the main drawbacks of these mechanisms is. This lack of consideration can result in the selection CHs that are either very close or very far away from the BS. If this occurs, it has a significant impact on the balance and distribution of CHs throughout the network. One of the main features for the proposed mechanism is that the new CH candidate selection process will ensure only those closest to the BS are considered, avoiding the problem of selecting the nodes with low energy for the CH role. Another unique feature proposed is the elimination of the frequent re-clustering process, which a considerable amount of nodes energy wasted.

In Chapter 6. The process of forming the clusters and topology structure in WSNs are crucial elements in sustaining network lifetime. This research proposed a new novel mechanism that aimed to fulfil the gap in well-known unequal clusters mechanism. The new mechanism provided a solution for the near BS clusters, where the two-level network constructed. The main achievements of the proposed mechanisms are; reduced the overhead produced by the number of the control message in other mechanisms, the cluster formation procedure requires few messages, more manageable structure for the network, reliable and scalable network. The local re-clustering process proposed in chapter 5 has been enhanced by introducing new levels re-clustering once the local re-clustering reaches its threshold.

7.3 Contributions summary

The cluster-based mechanism in WSNs provides an energy-efficient form of routing, reliable data transmission and scalable sensor networks. This research aimed to design new mechanisms that are an energy-efficient, scale well with any number of sensor nodes and extend network lifetime while taking into account the constrained resources of the nodes. This thesis introduced a three new cluster-based routing algorithm that meets the above requirements. The experimental results show that the proposed mechanisms outperform its counterpart mechanisms in meeting these aims due, largely, to its effectiveness in solving the problem of CH selection and developing a new method of cluster construction in WSNs. The findings are encouraging in term of the energy-efficiency savings achieved, as well as the scalability and reliability of the network. This research has demonstrated that the proposed mechanisms can be applied to different types of WSNs.

It is noteworthy to mention that the contributions presented in chapter 4, 5 and 6, cannot be combined in one major mechanism because of each contribution designed to target a specific gap. In chapter 4, the goal is to select the cluster head nodes and to fulfil the gap in the probability's selection of CH selection, where the CH nodes randomly selected. In chapter 5, the major goal is to develop a network that is fully distributed, and the nodes can be deployed in any area at random distribution. Moreover, the network uses a multi-hop manner to forward the data, which's different than the contribution presented in chapter 4. While in chapter 6, the new mechanism uses a different technique to construct the whole network, where the deployment domain is divided into two unequal levels. The goal for this new technique is to achieve high network reliability by forming a manageable structure for the network.

7.4 Future work

Wireless Sensor Networks offers many opportunities to adopted new applications for different technologies and fields. The growing interest in developing new applications for the Internet of Things, which mainly focuses on sensor devices. This has opened up new possibilities in sensor node research. However, the current constraints of sensor nodes have slowed progress in integrating these two technologies. In this section, a brief description of some possible future directions for this research presented.

7.4.1 Nodes battery: At present, in most WSNs applications, sensor nodes are powered by batteries. Changing or recharging node's batteries is not feasible, especially in cases where applications are deployed in harsh areas. Future research will certainly continue to focus on this area. Developing a new energy source, possible through energy harvesting, is one example of this, which can be adopted for the new proposed structures.

7.4.2 Multiple Base Station: In the simulation experiments of this research, the number of base stations assumed is single static base station as in most of existing cluster-based WSNs architecture reviewed in section 3.5, and that single base station is trustworthy. Considering only one base station in the proposed mechanisms of this thesis can be justified by fair comparison of obtained experiments results. Moreover, a single base station for WSNs applications is used for data collection when utilising multi-hop forwarding among the clusters. In these applications, the number of base stations always depends on the deployment area covered and the communication range of the sensor nodes. However, in some WSNs application, it requires multi BS, if the covered area is large and its more than the transmission range of the node. The sensor nodes can communicate directly with each other by wireless links and act as data forwarder over multi-hop manner to the base station. In small scale networks, all the nodes communicate directly with the base station in single-hop manner as in first mechanise presented in chapter 4. Considering multi-base station can be one possible future work for the proposed mechanism as well as mobile base stations.

7.4.3 Cluster-head selection: In this contribution, most of the possible scenarios for the available research resources have been considered; however, other scenarios have not been considered as they were out of the scope of this research such as mobile nodes and the mobile sink node. These represent some possible developments that can be applied in the future, ensure the applicability of the proposed mechanisms for mentioned scenarios.

7.4.4 Real-life testing: Due to the limited resources available for this research, all the experiments were conducted by using simulators. One possible direction for future research is to test the proposed mechanisms with real hardware, which can ensure the suitability of these mechanisms under different conditions that are not considered in the experiments.

7.4.5 More simulations experiments: As mentioned earlier, the limitation of the resources to conduct more complex experiments, such as Hardware, (super powerful PCs) that can handle heavy experiments were not available. However, all the experiments present in this thesis were tested under similar conditions and scenarios that were applied for the counterpart algorithms compared with the proposed mechanisms.

This thesis concludes by stating that, within WSNs, the conservation of node energy is just one feature of the system's problem; it is a philosophy that goes beyond that by considering all the aspect of system functionalities, including environmental parameters.

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