ADAPTIVE ENERGY MANAGEMENT MECHANISMS FOR CLUSTER BASED ROUTING IN WIRELESS SENSOR NETWORKS

Mohamed Eshaftri

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Abstract

Wireless Sensor Network (WSN) technology has been one of the major avenues of Internet of Things (IoT) due to their potential role in digitising smart physical environments. WSNs are typically composed of a vast number of low-power, low–cost and multifunctional sensor nodes within an area that automatically cooperate to complete the application task. This emerging technology has already contributed to the advancement of a broad range of applications. Nevertheless, the development of WSNs is a challenging issue due to significant concerns, which need to be resolved to take full benefit of this remarkable technology. One of the main challenges of WSNs is how to reduce the energy consumption of a single node, in order to extend the network lifetime and improves the quality of service. For that reason, a newly design energy efficient communication protocol is required to tackle the issue.

The clustering protocols designed for communication are alleged to be one of the most efficient solutions that can contribute to network scalability and energy consumption in WSNs. While different clustering protocols have been proposed to tackle the aforementioned issue, those solutions are either not scalable or do not provide the mechanisms to avoid a heavy loaded area.

This thesis presents new adaptive energy management mechanisms, through which the limited critical energy source can be wisely managed so that the WSN application can achieve its intended design goals. Three protocols are introduced to manage the energy use. The first protocol presents an intra-cluster CH rotation approach that reduces the need for the execution of a periodical clustering process. The second protocol relates to load balancing in terms of the intra and inter-cluster communication patterns of clusters of unequal sizes. This proposed approach involves computing a threshold value that, when reached, triggers overall network re-clustering, with the condition that the network will be reconfigured into unequal cluster size. The third protocol proposes new performance factors in relation to CH selection. Based on these factors, the aggregated weight of each node is calculated, and the most suitable CH is selected. A comparison with existing communication protocols reveals that the proposed approaches balance effectively the energy consumption among all sensor nodes and significantly increase the network lifetime.

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List of Acronyms

ACQUIRE	Active Query Forwarded in Sensor Networks
ADC	Analogue and Digital Converters
APTEEN	Adaptive Periodic-TEEN
ARQ	Automatic Repeat Request
BFS	Breadth-First-Search
BS	Base Station
CCH	Candidate Cluster Head
CH	Cluster Head
CM	Cluster Member
DARPA	Defence Advanced Research Projects Agency
DD	Directed Diffusion
DEEC	distributed multilevel clustering algorithm for heterogeneous WSN
DLCP	Dynamic Load-balancing Cluster-Based Protocol
DWEHC	Distributed Weight-based Energy-efficient Hierarchical Clustering
EEHC	Energy Efficient Hierarchical Clustering
EEMC	Energy-Efficient Multi-Level Clustering
EEUC	Energy Efficient Unequal Clustering
ETSI	European Telecommunications Standards Institute
FCH	Final Cluster Head
FEC	Forward Error Correction
GAF	Geographic Adaptive Fidelity
GBR	Gradient-Based Routing
GEAR	Geographic and Energy Aware Routing
GPSR	Greedy Perimeter Stateless Routing
HCC	Hierarchical Control Clustering
HEED	Hybrid Energy-Efficient Distributed
HT	Hard Threshold
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
LCP	Load-balancing Cluster Based Protocol

LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	LEACH-Centralized
LPC	Load-balancing Cluster-Based Protocol
MAC	Media Access Control
MOCA	Multi-hop Overlapping Clustering Algorithm
MWE	Multiple Winners
NID	Node Identification
OBM	Ordinary Broadcast Mechanism
PEACH	Power-Efficient and Adaptive Clustering Hierarchy
PEACH	Power-Efficient and Adaptive Clustering Hierarchy
QoS	Quality of Service
RECA	Reputation based Clustering Algorithm
R-HEED	Rotated Hybrid Energy-Efficient and Distributed
RUHEED	Rotated Unequal HEED
SAR	Sequential Assignment Routing
SCH	Sort Cluster Head
SMP	Sensor Management Protocol
SN	Sensor Node
SPEED	A Stateless Protocol for real-time communication in sensor network
SPIN	Sensor Protocols for Information via Negotiation
SQDDP	sensor query and data dissemination protocol
ST	Soft Threshold
SWE	Single Winner
TBF	Trajectory Based Forwarding
TCCA	Time Controlled Clustering Algorithm
TCH	Threshold Cluster Head
TDMA	Time Division Multiple Access
TEEN	Threshold-sensitive Energy Efficient sensor Network
UHEED	Unequal version of HEED
WDCR	Weight Driven Cluster Head Rotation
WSNs	Wireless Sensor Networks

List of Publications

1. M. Eshaftri, A. Essa, M. Qasem, A. Y. Al-Dubai, and I. Romdhani, 'Reliable Hierarchical Cluster-Based Routing Protocol for Wireless Sensor Networks' Advanced Networking, Distributed Systems and applications (INDS 2014), Béjaia (Algeria), 2014, pp. 21–26.

2. M. Eshaftri, A. Y. Al-Dubai, I. Romdhani, and M. B. Yassien, 'A new energy efficient Cluster Based Protocol for Wireless Sensor Networks', Computer Science and Information Systems (FedCSIS), IEEE 2015 Federated Conference on, Lodz, 2015, pp. 1209–1214.

3. M. Eshaftri, A. Y. Al-Dubai, I. Romdhani, and M. B. Yassien, 'An Efficient Dynamic Load-balancing Aware Protocol for Wireless Sensor Networks'. MoMM'15 Proceeding of the 13th ACM International Conference on Advances in Mobile Computing & Multimedia, At Brussels, Belgium, 2015, pp. 189–194.

4. M. Eshaftri, A. Y. Al-Dubai, I. Romdhani, and A. Essa, 'Weight Driven Cluster Head Rotation for Wireless Sensor Networks'. MoMM'16 Proceeding of the 14th ACM International Conference on Advances in Mobile Computing & Multimedia, At Singapore, Singapore, 2016, pp. 327–331.

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Declaration

I, Mohamed Eshaftri, 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.

Name: Mohamed Eshaftri

Matriculation Number: 09007807

Signature: Date: 20/03/2017

Chapter 1

Introduction

1.1 Research Background

D evelopments in information technology are increasingly affecting industries and the lifestyles of communities. Indeed, this can be seen to be paving the way towards the fourth industrial revolution (Industry 4.0) [1]. The physical world is becoming integrated into information systems via smart sensors embedded in physical environments that communicate through wired and wireless networks and Internet protocols. Such systems are often associated with the Internet of Things (IoT) concept [2]. Smart roads, smart parking, smart homes, intelligent transportation, etc., are infrastructure systems that are making our world more connected than was ever thought possible.

The idea of the IoT was developed alongside the technology of Wireless Sensor Networks (WSNs) [3, 4]; this brings IoT applications greater abilities in terms of both sensing and activating. A WSN can be defined as a network composed of low-power, low-cost, multifunctional sensor nodes (SNs). These nodes can be either densely or sparsely deployed to observe physical environmental conditions, such as pressure, temperature, sound, etc. [5]. To enable remote monitoring of an environment, SNs must send the gathered data through wireless links in a hop-by-hop manner to a distant base-station (BS) [6]. The BS can then transfer the data using a wired or a wireless internet connection to an end user, usually located outside the sensing field, as Figure 1.1 illustrates. The first developments in the application of WSNs were motivated by the US military [7]. Examples of applications related to this include battlefield surveillance. Now there are a great variety of WSN applications, all with unique characteristics and requirements that are used in a variety of fields including, but not limited to health care, agriculture, intrusion detection, inventory/motion tracking, and security [8, 9, 10].
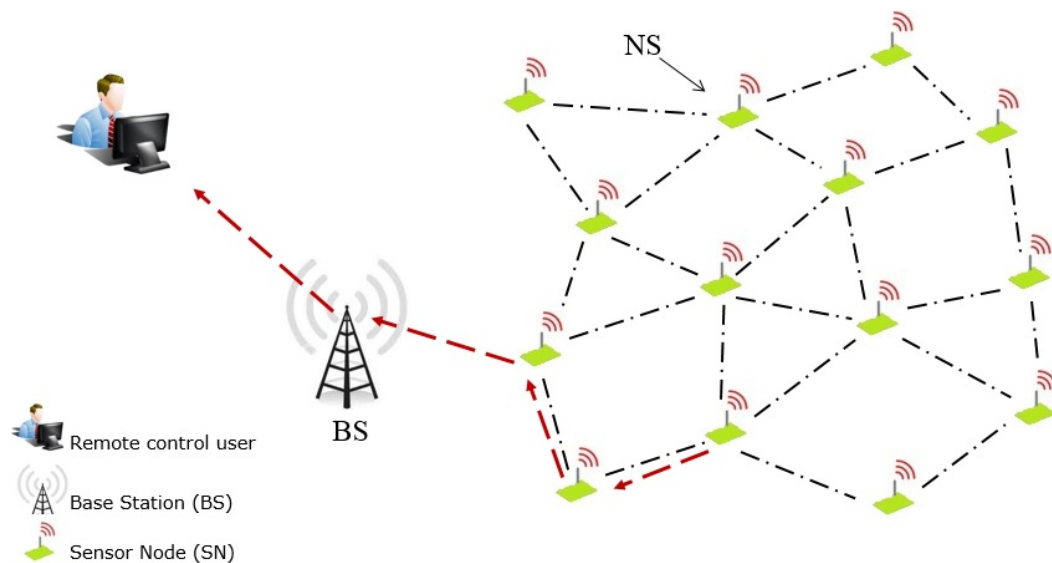
Figure 1.1. General wireless sensor network architecture.

This diversity of applications has attracted the interest of many people in the research community and of standardisation bodies, such as European Telecommunications Standards Institute (ETSI) [11], Internet Engineering Task Force (IETF) [12], IPOS-Alliance [13], and Institute of Electrical and Electronics

Engineers (IEEE) [14]. These latter organisations place a great deal of emphasis on the design of applications, which may be important to the sustainability, efficiency, and safety of society, now and in the future. However, the development of WSNs is still at an early stage. To fully benefit from this remarkable technology, several issues must be resolved. Due to the very strict energy constraints and the fact that battery replacement is impossible in many cases, one of the critical issue related to WSNs is how to reduce the energy consumption of a single node [15, 16]. Indeed, such a reduction would significantly improve network lifetimes and reduce the costs of implementation.

1.2   Motivation

In general, WSN applications are expected to be easily deployable, possibly in harsh and extreme environments (e.g., remote areas [17], inhospitable habitats, or other regions presenting risks to the technology [18, 19]). Therefore, it is very important that SNs can communicate with each other even in cases of network infrastructure failure. Because WSN nodes may be randomly deployed with no location awareness, SNs need to be self-configuring without the use of an overall control mechanism that sets up and/or maintains the network infrastructure. Moreover, since each SN will generally undertake significant data sensing, processing, and communications tasks, the impairment of the function of just a few nodes can affect the functionality of the application and the network lifetime [20]. Thus, all aspects of SNs, from the sensor module to the other hardware and protocols involved, need to be planed and designed in a highly energy-efficient manner to extend the network lifetime.

In fact, several research studies have been devoted to examine the challenges faced by WSNs, and energy conservation has emerged as the most challenging issue [21]. Although various energy-aware routing protocols have been developed, these have not solved the problem. The key function of a routing protocol is to create the network topology. Included in this are the mechanisms for finding feasible paths whereby data packets can be transferred from the source to destination node, for re-establishing or repairing any broken paths and for minimising bandwidth utilisation [22]. The routing protocols used by WSNs are usually divided into two main types: flat routing and cluster-based routing protocols. In flat-routing protocols, as

demonstrated in Figure 1.2, all SNs have the identical functionality, and they all function simultaneously both to perform sensing and to route the data within the network [23]. Thus, a considerable communication overhead occurs, which leads to high energy consumption across the whole network. Examples of flat-routing protocols are Sensor Protocols for Information via Negotiation (SPIN) [24], Sequential Assignment Routing (SAR) [25], rumour Greedy Perimeter Stateless Routing (GPSR) [26], Directed Diffusion (DD) [27], Energy-Aware Routing (EAR) [28], Trajectory Based Forwarding (TBF) [29], and Gradient-Based Routing (GBR) [30].
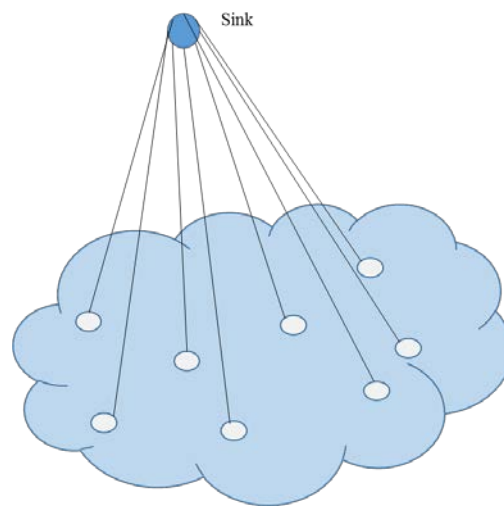
Figure 1.2. Flat-based routing architecture.

In the alternative, cluster-based routing as demonstrated in Figure 1.3, the network is subdivided into a set of administrative units called clusters. These are formed by a group of nodes identified as being within the boundaries of a cluster. Each cluster is managed by a designated node, which is known as the cluster head (CH). The main objective of a CH is to aggregate the data from the cluster member (CM) nodes within the same cluster group and transmit this data to the next hop until it reaches the BS [31]. Thus, more energy is saved since only the CH needs to be constantly active, while the other SNs spend much of the time with their radio transceivers turned off. Moreover, this data aggregation technique might decrease the amount of data packets that need to be forwarded. Cluster-based protocols outperform flat protocols and have become a prominent part of WSN routing technologies [32].
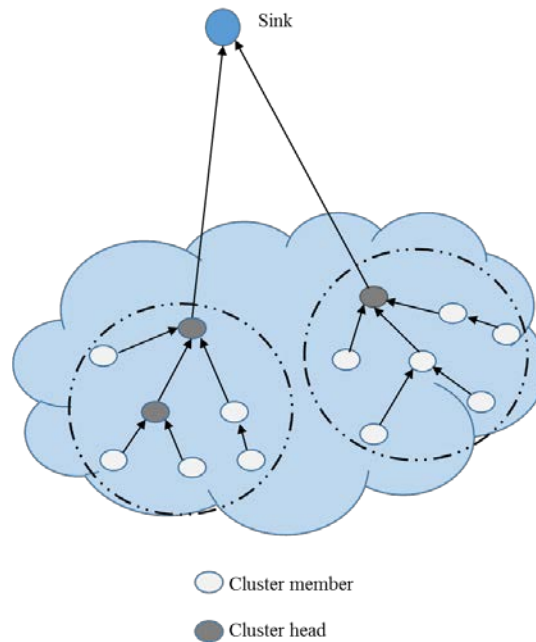
Figure 1.3. Cluster-based routing architecture.

This thesis will explore new approaches to network lifetime maximisation for WSNs. This work is motivated by the absence of any protocols in the literature that do this effectively, despite the advantages that some protocols appear to offer in this regard. The theoretical advantages and classifications of all the current cluster-based protocols will be discussed fully in Chapter 3.

1.3   Problem Definition

Despite the advantages of the cluster-based routing protocols that have been proposed in the past, there are still issues that need to be addressed to minimise energy consumption and consequently increase network lifetimes. The issues that can be identified are as follows.

First, in cluster-based protocols, CHs are responsible for receiving and aggregating the data from their CMs and transferring this data to its identified destination [33]. Thus, the energy usage of the CHs is greater than that of the CMs. Additionally, when the CHs send aggregated data to the BS, such long-distance transmissions will use up significant amounts of energy and cause the premature deaths of CHs [34]. It

is noteworthy that, although many different clustering techniques were introduced to enhance the performance of the network, only a small number of researchers have addressed the rotation technique. The rotation technique, as related to cluster-based routing protocols, divides the lifetime of the WSNs into a number of 'rounds', as shown in Figure 1.4. In each round, new CHs must be selected to rotate the CH role among the nodes available according to an appropriate clustering. Rotating the role of the CH equally among the nodes results in improvements in load balancing, and this extends the network lifetime [35]. However, as each round of CH rotation is executed across the whole network, a large overhead is incurred every time the clusters are reformed, which itself leads to excessive energy waste. To overcome this
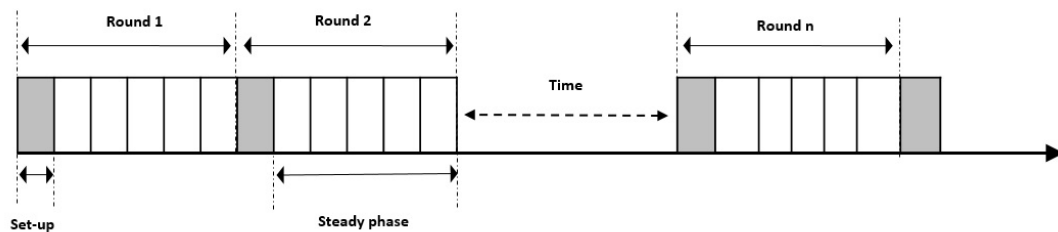
Figure 1.4. Timeline of the spent round.

problem, it is essential to determine concrete techniques in order to manage the energy consumption and increase the network lifetime.

Second, cluster-based routing protocols for WSNs often suffer from inequitable distributions of CH nodes within a network. This can cause increased energy waste [36], lead to an imbalance in energy consumption among the clusters, and affect overall network performance. Therefore, equitability in terms of load distribution is a crucial aspect that needs to be considered when designing a cluster-based routing protocol.

Third, in cluster-based protocols, CHs consume extra energy when they perform network processes, and this can lead to the early death of such nodes and cause network failure. The selection of an optimal CH can greatly affect the energy efficiency of the network. A CH can be 'elected' based on node quality. This can be based on several diverse metrics, such as residual energy, node degree, connectivity,

and the distance of the node from its neighbours [37]. Significant improvements in performance and quality may be achieved by combining these metrics.

1.4   Aims and Objectives

This thesis focuses on clustering techniques for WSNs in order to develop a self-organizing and energy management routing protocol for continuous monitoring applications in WSNs with minimum overhead. The aim of this research is to develop a set of adaptable routing protocols that will collect the sensed data energy efficiently, and will be able to adapt and reconfigure autonomously in conjunction with the changes of the network conditions. In order to achieve the above aim, the following objectives were set up:

Research Objectives

- Obtain an in-depth knowledge and understanding of WSN theory and widely comprehend the principles related to WSN clustering techniques. Investigate the major issues and concerns related to cluster-based routing protocols.

- Design a routing protocol that reduce the periodical clustering process. This is believed to reduce the overhead control massage and enhance the performance of the network lifetime.

- Design an adaptive routing protocol that uses an adjustable round time, when the network will be of an unequal cluster sizes in order to load balance intra and inter cluster communication.

- Design a new performance factors for the CH selection based on an original combination of metrics. This is believed to improve the performance and quality of the networks.

1.5   Contributions Made in the Thesis

The main contribution of this thesis is the proposal and analysis of a novel energy aware clustering protocols, which reduce the control message overheads and

balances the intra and inter cluster communication resulting in longer network lifetime. These contributions are briefly outlined in following section.

- **Contribution one - The CH role rotation technique:**

The first contribution is the proposal of New Load-balancing Cluster-Based Protocol (LCP), which introduces a new inter-cluster head rotation approach. In LCP the nodes are randomly deployed in a large sensor field and unaware of their location. LCP is fully distributed protocol, where the nodes independently configure and form the network topology. CH in each cluster is selected based on the highest residual energy. Therefore, by rotating the cluster head task within each cluster rather than re-clustering the global network, the LPC reduces the clustering process overheads.

- **Contribution two - An adaptive round time controller:**

The second contribution builds on and improves the LPC by proposing Dynamic Load-balancing Cluster-Based Protocol (DLCP). The DLCP provides a pre-defined interval timer at the beginning of every round for selecting the CH. This delays the frequency of re-clustering message triggered by the BS. The CHs continue to rotate the leadership among the nodes within the same cluster, by selecting the node with the highest residual energy in each round. When the energy of CHs falls below a fixed threshold (T_{CH}), a new clustering process is initiated. This process balances intra and inter-cluster communication and reduces the energy waste.

- **Contribution three - Parameter based CH election:**

The third contribution the Weight Driven Cluster Head Rotation (WDCR) protocol continues the advancement of the two former protocols. Firstly the WDCR selects the CH based on the following factors: residual energy; distance of the node from the BS; and the number of time the node being selected as a CH. The weight of the node is calculated based on these three factors and the node with the highest weight is selected as a CH. Secondly, alike in the DLCP the unequal size of the clusters are formed and thirdly the intra cluster head rotation is applied.

1.6   Thesis Structure

This section outlines the structure of the thesis and provides a short summary of the work undertaken regarding each chapter.

- **Chapter Two – Background**

This chapter outlines the necessary background that is required to understand the research problems discussed in the literature review. This discussion includes the definition of WSNs, their application, and the key issues associated with them, such as energy consumption.

- **Chapter Three – Literature Review**

This chapter provides an overview of the recent literature regarding the clustering techniques that are deployed by WSN routing protocols. Additionally, it discusses the important issues which should be considered when designing cluster-based protocols. Moreover, existing energy-efficient clustering protocols are discussed.

- **Chapter Four – Load-balancing Cluster-based Protocol (LCP)**

This chapter outlines how the first contribution of this study (as given above) is to be achieved. It presents and examines a new algorithm, the load-balancing cluster-based protocol (LCP), which significantly reduces the energy consumption and improves the lifetime of a network.

- **Chapter Five – Dynamic Load-Balancing Cluster-Based Protocol (DLCP)**

This chapter describes the second research contribution that this study will make. It will make this contribution by proposing an improved version of the previous protocol. This improved version is the dynamic load-balancing cluster-based protocol (DLCP). This protocol reduced energy consumption and further improved network lifetime.

- **Chapter Six – Weighted Cluster-based Protocol (WDCR)**

This chapter describes the work that fulfils the requirements of the third contribution. It provides an account of an improved version of the previous protocol. This final improved version is called the weight-driven CH rotation in distributed wireless sensor network (WDCR) protocol. This protocol reduces the energy consumption of networks and further improves their lifetime.

• **Chapter Seven – Conclusion**

This chapter concludes the dissertation by summarising its findings and discussing the major issues that have been addressed and possible future directions for research.

Chapter 2

Wireless Sensor Networks

T his chapter outlines the necessary background for understanding the research problem discussed later in the literature review by outlining the theoretical concepts and practical aspects of WSN technology and applications. The chapter starts with the definition of the SN and the description of its components. Furthermore, the practical usage of WSN applications is discussed, as well as the classification of the applications is presented alongside the basic architectural framework. The chapter concludes with the presentation and visual demonstration of the routing technologies in the WSNs and their classification.

2.1   General Sensor Node Structure

WSNs are composed of many SNs. Each SN has ability to gather and process sensory information, and communicate with other related nodes in the WSN field [6]. A SN consists of four fundamental elements, as demonstrated in Figure 2.1: a sensing unit, a processing unit, a transceiver unit, and a power unit [16, 20, 38, 39], which will be described in turn as follows.
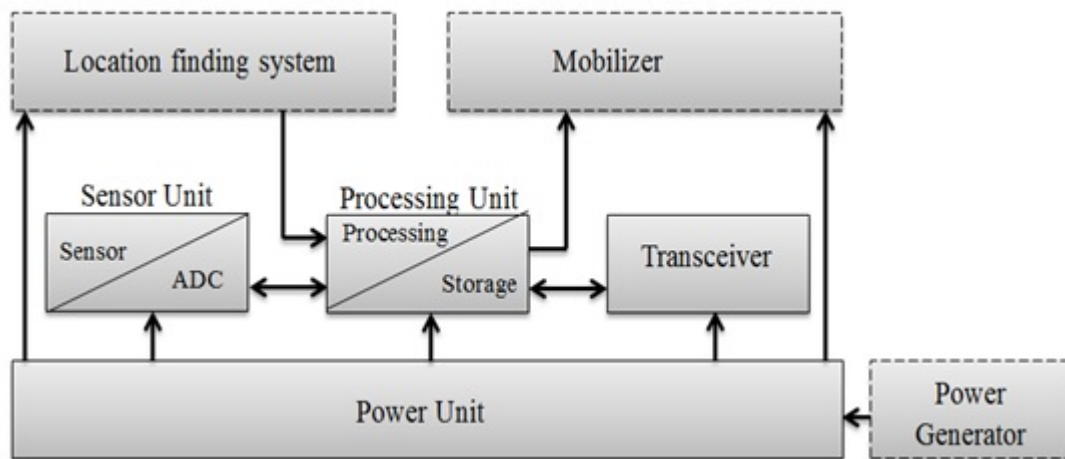
Figure 2.1. Components of sensor node.

2.1.1   Sensing Unit

A sensing unit consists of two subunits, sensors and analogue to digital converters (ADC) [16]. The task of the sensing unit is to convert the specified target or environment to digital signals and then divert it into the processing unit. Depending on the type of application, SNs could also have other subunits, for example, location finding system unit, mobiliser unit, camera unit, and power generating unit.

2.1.2   Processing Unit

This unit is the microprocessor element of a SN and is responsible for executing most of the instructions that make the SNs cooperate with each other and perform given functions. Such functions might be; turning on the sensor, converting the target data to digital equivalents, and aggregating and storing data in the memory for further processing [20].

2.1.3   Transceiver Unit

This unit enables the connection of the nodes within network for transmitting and receiving the information at the same time [38].

2.1.4   Power unit

This is the main source of energy for the SN. The power unit is also called the battery. In most applications, the battery is the only source of energy. However, some applications might be reinforced by a power scavenging unit based on vibration, solar, or wind power [40].

In WSNs, the nodes typically cover a large geographical area and are required to function over a long period. Since each SN runs on a battery, the preservation of energy of each node within the network must be considered when designing the WSN applications.

2.2   Wireless Sensor Networks Applications

The WSN applications are generally classified according to their delay requirements starting with real-time applications, which require a minimum delay to provide an immediate response to any event [40], followed by applications where the important requirement is that the data are successfully received by the server irrespective of the time taken for the transmission to occur. According to [41], applications might be categorised into two groups: monitoring and tracking, as Figure 2.2 demonstrates. Some of the applications of WSNs are described below.

2.2.1   Military Applications

WSNs were first developed for military use in 1978 by the Defence Advanced Research Projects Agency (DARPA) [42]. DARPA has focused on WSN research challenges. Some of the military applications of WSNs that DARPA has focused on are as follows.

- **Monitoring friendly forces equipment and ammunition:** WSNs were used to monitor the status of friendly troops and to enable troop leaders to keep track of the condition and availability of ammunition and equipment on the battlefield.

- **Battlefield surveillance:** WSNs were also used for the surveillance of critical terrains, paths, and straits to help implement new operational plans in the battlefield.

- **Nuclear, biological, and chemical attack detection and reconnaissance:** The WSNs served as warning systems advising teams on the ground of the threat of nuclear radiation or in the event of chemical and biological warfare.
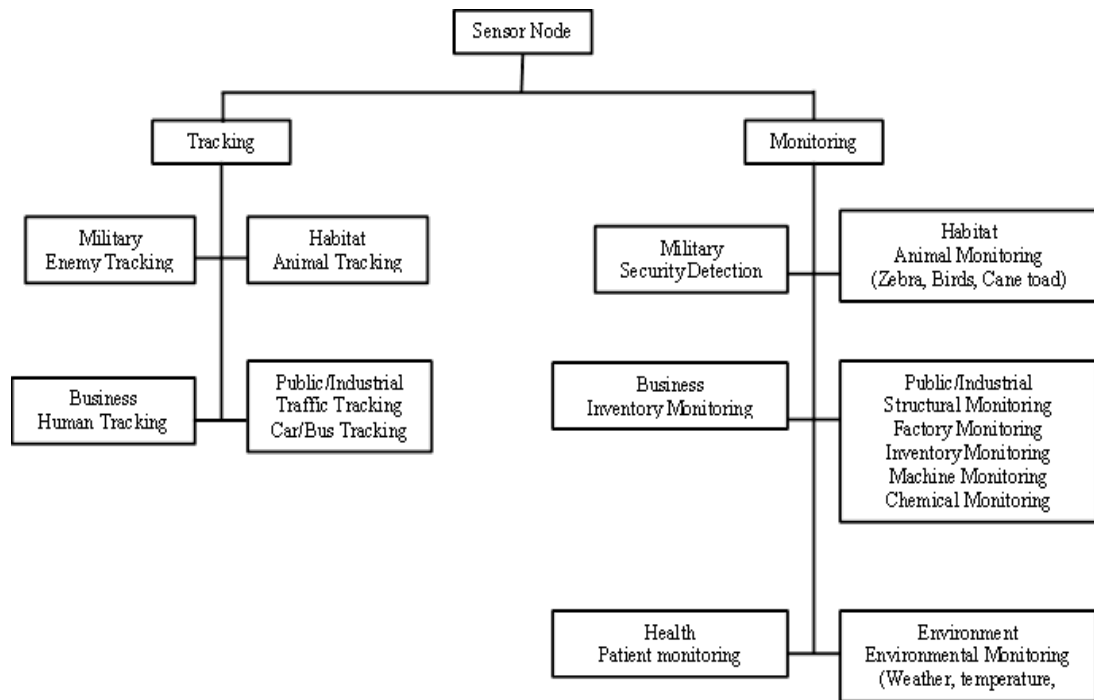
Figure 2.2. Wide range of WSN applications [41].

2.2.2   Industrial Control

The WSNs that are deployed for industrial purposes can be classified according to their application requirements. Event-driven applications respond to actions generated by the user or the system, such as changes in machine processes, plant security, and operator actions. Data-driven applications can be used for tracking material flows, such as particle detection in flowing liquid [43, 44], thus helping to reduce human error and labour costs and prevent costly manufacturing downtime. Factories can be monitored for controlling some tasks as well as for security reasons.

- **Smart Infrastructure:** WSNs are widely used in industrial areas of

infrastructure, for example in the form of smart infrastructure WSNs. Many countries including the USA, Europe and China are devoting large financial resources to improve transport and monitoring the infrastructure. WSNs are used for monitoring the quality and safety of road surfaces, stability and corrosion of bridges, safety and condition of power lines and lighting operation [45]. WSNs are also able to measure visibility, gases and airflow, when deployed in tunnels [46]. Indeed, WSNs are a key element in intelligent transportation systems, where the roads and vehicles can exchange information to promote road safety and driven experience. Moreover, in the smart city paradigm, WSNs play potential roles.

- **Traffic Congestion:** The use of WSNs helps to prevent and manage the daily challenges of highway traffic congestion. Smart sensors monitor vehicles on the highway and reduce traffic in the rush hour by giving information about the speed, nearest exits and road junctions [47]. Usage of WSNs to assist city traffic informs drivers about any active road works in the city and the nearest available parking places. Furthermore, the nodes have ability to carry small cameras, which serve as surveillance tools for observing the traffic and actions on the road. From the above it is indisputable that the use of WSNs in the transport infrastructure may lead to a better and safer usage of the roads [48].

2.2.3 Surveillance

Early surveillance systems were used to monitor behaviour and activities. In such systems, a camera is wired to a central server into which it feeds a continuous data stream. [49, 50]. Recent research has focused on smart wireless cameras that can easily be deployed to observe large areas, such as public parks, airports, and railway stations and send raw data to a central server, communicating with each other and the central server through a wireless system. Such systems can also be used to read remote water meters.

2.2.4 Environmental Monitoring

Using WSNs in environmental context can prevent national disasters by monitoring

the following areas:

- **Active volcano**: Monitoring of an active volcano is the domain of a WSN environment application. It used to be very expensive to monitor an active volcano by employing expensive devices that were difficult to move and needed an external power supplier. [51] Using WSNs for active volcanos has proved to be very useful, as a large number of small and cheap no discover a wide area powered by an internal battery can be deployed. [52]

- **Forest fire detection**: The SNs can be randomly spread by the helicopter in the forest. Powered by solar cells, they can wirelessly collaborate with each other and detect the fire promptly before it spreads widely[53].

- **Monitoring air pollution**: Research shows that around 1600 people die from breathing polluted air in Spain, where traffic is responsible for 80% of pollution. WSNs have become important in providing information on the areas with the highest pollution [47, 54].

- **Wireless sensor networks to detect floods**: Water flooding is one of the most frequent natural disasters. At least 700 deaths have been caused by floods in Europe since 2000 [47]. Manual reading is one of ways of predicting floods but it is not always possible for a person to measure water level close to a river as the monitors could put themselves in danger. WSNs are the key solution for detecting early flood signs. WSN nodes can be deployed in water and will monitor any change in water level. [55]

- **Smart Agriculture**: WSNs are modernizing the current traditional methods of agriculture. [56] WSNs can be used to maximize agricultural results by monitoring different environmental parameters related to agriculture. For example, WSNs are used to measure the moisture and temperature levels in compost to avoid mould and other bacteriological toxins [57]. In addition, WSNs can be used to monitor and control the tracking of food containers being shipped from other countries. They can be also used inside glasshouses to supervise the right temperature.

2.2.5   eHealth

E-Health is another exciting area of the use of WSN applications. Smart wireless cameras could be used to enhance the treatment and care of people in hospitals and old peoples' homes as well conditions of people with disabilities. Using SNs in e-health enables monitoring of the medical state of a patient. Sensors deployed in a patient's body will provide information about the oxygen in blood, airflow, body temperature, blood pressure, glucose level and patient position [58]. WSNs can also help the patient in indicating administration of the correct medicines at the right time and reducing adverse drug events, by attaching a node to the patient's medicine drip feed [59]. Figure 2.3 demonstrate an eHealth WSN application infrastructure.
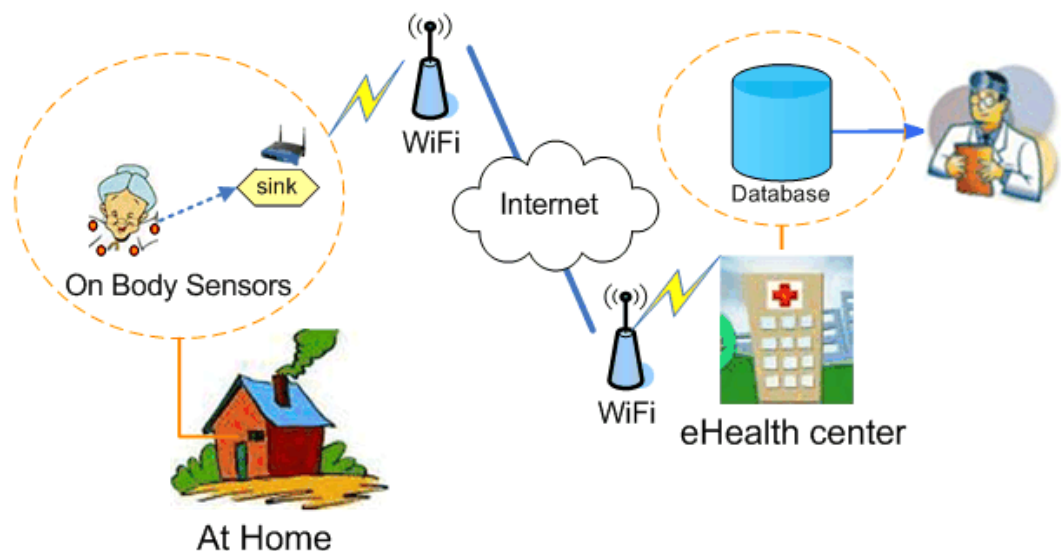
Figure 2.3.eHealth WSNs application [61].

Additionally, WSNs could be deployed to send relevant personal health information to relevant authorities for their immediate attention. Such application could become indispensable in case of an emergency [60].

2.2.6   Virtual Reality

Smart cameras can be deployed to observe remote areas or areas of historic interest, providing real-time information to authorities. Users would be able to observe

locations from different angles and to zoom in and out [61]. In another application, a network of cameras could be used to create the feeling of being in a real meeting room situation for a person who is participating in a virtual meeting [62].

It is evident from the above outline that WSN applications impact many areas of human life and have diverse uses and benefits. Nevertheless, to fully benefit from this remarkable conception and to design energy-efficient applications in WSNs, deeper understanding of the architectural framework of WSNs is required and will be discussed in the following section.

2.3   Challenges and Constraints of WSNs

WSNs have remarkable prospects to monitor and cooperate remotely with the physical world. As mentioned previously WSNs consist of battery-powered sensor nodes with a multitude of features depending on the WSN applications. Although sensors have the ability to gather vast amounts of data, they also operate under a set of distinctive constraints. For WSNs to become truly ubiquitous, it is vital to comprehend the design challenges of the WSNs in order to incorporate energy efficient protocols in particular situations.

2.3.1   Energy constraints

A great amount of research has been devoted to the discourse of WSNs challenges, from which energy conservation emerges as the most challenging issue [40]. WSN nodes require a constant source of energy to perform various operations. However, the SNs have restricted energy capacity as they depend on limited life batteries. Additionally, according to [16] [62], in many applications the replacement of the battery is impossible due to the accessibility of the nodes. In multi-hop sensor networks, each node performs two tasks; data gathering and data routing. Therefore, the impairment of the function of a few nodes due to battery dysfunction can affect the network lifetime.

2.3.2   Wireless Networking

A substantial amount of energy is used during the processing and communication of large amounts of data by the SNs especially in large scale networks [63].

Consequently, more energy is required to transfer the information to the BS. To split the large distance into several shorter distances, in which the nodes are required to communicate with their neighbours, can lead to substantial energy saving. This multi-hop communication demands the nodes in a network cooperate with each other to find effective paths and to serve as relays. [64]. Another technique use to save the energy of the nodes during the data transition is adaptive duty cycling [16]. Most of the SNs are in a sleep mode for a period of time and unable to receive the messages from neighbours, while some nodes in the network remain active.

2.3.3   Decentralized Management

The reliance on centralized algorithms to implement network management solutions represents another challenge in WSNs. A BS can gather the information from all the nodes, establish optimal routes, and inform nodes of its route [65]. However, the amount of energy consumed during this process can be significant accounting for frequent topology changes. The networks should be able to be easily adapted, and protocols must thus scale well with the number of nodes. This is often achieved by using distributed and localised algorithms, where sensor nodes only communicate with nodes in their neighbourhood and make the decision based on local information without global knowledge [66].

2.3.4   Self-Management

Many WSNs applications operate in remote and harsh environments. To maintain the functionalities of the overall task in the face of any interruption such as physical damage or environmental interference, WSNs should be able to operate without the need for manual configuration [67]. Part of the solution could be a self-managing device that will monitor its environment, adapt to changes in the environment, and collaborate with its neighbour nodes to form topologies or decide on sensing, processing, and communication strategies [56].

2.3.5   Design Constraints

The primary goal of wireless sensor design is smaller, cheaper, and more efficient devices. The cost of an entire network is justified by the cost of the single node. Most of the sensor network applications contain a large number of SNs. Thus, the

cost of each SN needs to be kept low [68]. Additionally, algorithms need to be simple in order to minimise computational complexity and memory usage and supportive in reducing energy consumption [69].

2.3.6   Real Time Operation

Some WSN applications, such as body area networks, which are monitoring patient physical parameters, such as blood pressure, heartbeat or level of sugar, require immediate data transmission from the SN to the server. However, data processing among the SNs and transmission over the wireless link can be affected by real time processing; available bandwidth; and limited energy resources. Therefore, delay requirements will depend on the use of application [70].

2.3.7   Security

Many WSNs gather confidential information in application of battlefield, surveillance, building monitoring, burglar alarms, airports and hospitals. Therefore, security and confidentiality is essential in WSNs to protect information exchange between the SN and BS. Part of the security requirement is the ability of the SN and BS to verify that the data received is coming from a trusted sender, as a false data can change the way a network could be predicted [71]. Although numerous security solutions have been proposed to prevent WSNs security attacks, many cannot be satisfied due to limited computational capacity, memory and power availability of the SN [72].

2.4   WSNs Architectural Framework (Protocol Stack)

To develop energy-efficient protocols, which will support diverse WSN applications; it is important to understand the software implementation of a sensor protocol. Figure 2.4 shows the protocol stack used by each SN and the BS. Each protocol layer perform specific functions but shares management planes [73]. The power management plane has responsibility to manage the usage of power of a SN. The mobility management plane senses and records the movement of SNs. The task management plane balances and programmes the sensing tasks [38]. Thus, some nodes with more power can perform the sensing task more than nodes with less power. Without these management planes, each sensor would work in isolation.

Therefore, the management planes are essential for SNs to collaborate in a power-efficient manner, route data in a mobile SN, and distribute resources among SNs [74]. Consequently, if SNs cooperate with each other, a significant amount of the resources can be preserved and the sensor network lifetime can be extended. The protocol stack comprises the application layer, transport layer, network layer, data link layer, physical layer, power management plane, mobility management plane, and task management plane [16].

2.4.1   Physical Layer

The physical layer is the first and lowest layer in the protocol stack. This layer defines the means of sending and receiving raw bits rather than logical data packets over the wireless channel connecting the nodes. It also executes numerous tasks, such as frequency selection, carrier frequency generation, signal detection, modulation, and data encryption [75].
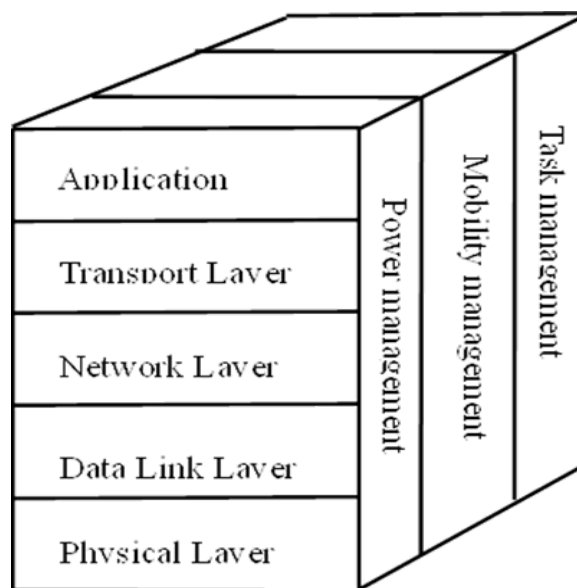
Figure 2.4. The wireless sensor networks protocol [74].

2.4.2   Data Link Layer

The data link layer is above the physical layer and its responsibility is applying the multiplexing of data streams, data frame detection, and medium access and error

control. It confirms consistent node-to-node and node-to-many connections in a communication network [74].

The Media Access Control (MAC) layer protocol in a wireless multi-hop self-organising sensor network has been designed to complete two aims. First, to create the basic infrastructure necessary for hop-by-hop wireless communication and to provide the self-organising capability by establishing communication links for data transfer over thousands of SNs. Second, to ensure the reliability and efficiency of network transmissions and share communication resources between SNs, such as time, energy, and frequency [56]. Error control is one of the important objectives of the data link layer. Types of error control communication networks include Automatic Repeat ReQuest (ARQ) and Forward Error Correction (FEC) [77]. ARQ is more commonly used in sensor networks. However, in comparison with FEC, it has more complexity in decoding and incurs additional retransmission cost and overheads.

2.4.3   Network Layer

The network layer is the backbone of the network where the routing takes place. The network layer main job is to discover routes between the SNs and the BS in multi-hop WSNs and to get packets from the source node to the destination. Therefore, according to [73, 78], the networking layer of sensor networks should be aimed to address the requirements of the sensor networks. Routing, for instance, ought to be highly energy efficient to prolong the network lifetime. Additionally, routing should support the Quality of Service (QoS) requirements in regards to communication latency and packet loss [79]. The network layer must be scalable in line with the network size, and routing should support the data-centric nature of sensor networks [80].

2.4.4   Transport Layer

The fourth layer is the transport layer, which is placed over the network layer to ensure end-to-end message transmission. When messages are broken into a number of segments at the transmitter, this layer passes them on to the network layer, where the data are routed to the receiver and reassembled into messages. The transport layer protocol design is challenging task in WSNs because the SNs are influenced by

hardware constraints, such as restricted power and memory [41]. The transport layer protocol takes care of two key requirements for WSNs, namely, reliability and congestion control [78].

2.4.5   Application Layer

The application layer is the only layer of the network stack that interacts with the user directly. This layer also includes different types of applications, including node localisation, query dissemination, network security, and time synchronisation. For example, the Sensor Management Protocol (SMP) is an application layer protocol, which is responsible for providing software operations for a variety of tasks, such as moving SNs, synchronising SNs, exchanging location-related data, scheduling SNs, and querying the status of SNs [20]. The Sensor Query and Data Dissemination Protocol (SQDDP) provides user applications with interfaces to issue queries, reply to queries, and gather responses [73, 74].

2.5   Routing Technologies in WSNs

The routing protocol is in charge of finding the right route to transfer the information packet from the source node to the destination node [79]. The destination node is generally named a sink node or a BS in WSNs [80]. However, in some WSN
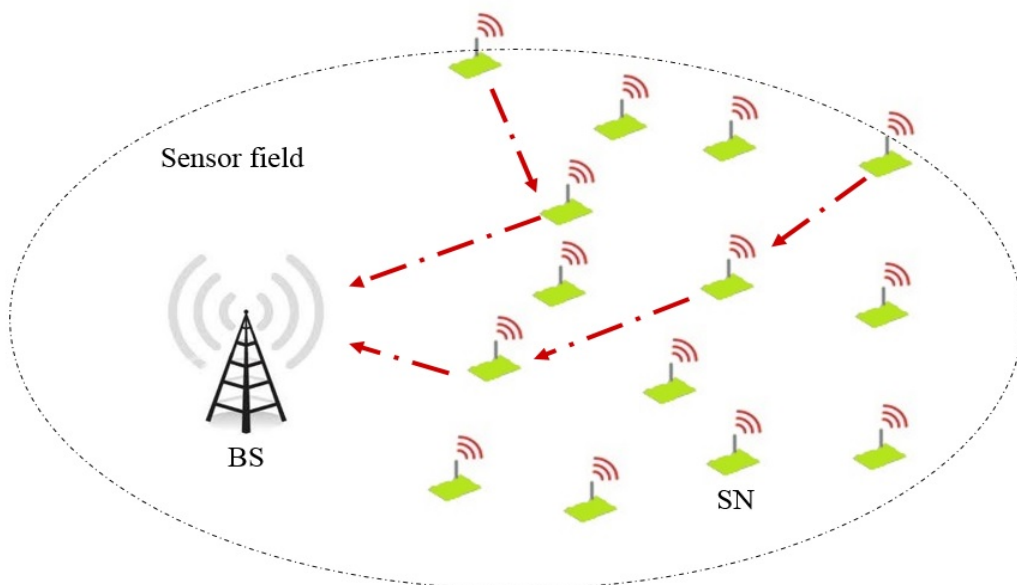
Figure 2.5. Communication path from a sensor to a sink node.

applications, the destination node can be located outside of the transmission range of that node. Thus, the data packet needs to travel through multiple-hops to reach the BS. Figure 2.5 shows transmission paths from SNs to the BS node. Moreover, the routing protocols in WSNs are different from those of fixed networks. In WSNs, no infrastructure is needed, and the SNs are sensitive to energy consumption. Therefore, strict energy saving requirements ought to be obey when designing WSN routing protocols.

According to [81], routing protocols might be categorised based on the type of routing communication used within the network for transferring the data from the source to the destination. The authors in [82] proposed three types of protocols in this classification: proactive, reactive, and hybrid. In proactive (table-driven) routing protocols, the nodes calculate all the paths and keep a list of destinations before the BS communicates with the nodes in the network. However, in reactive (on demand) routing protocols, the nodes find a path on demand, only when the BS requests data
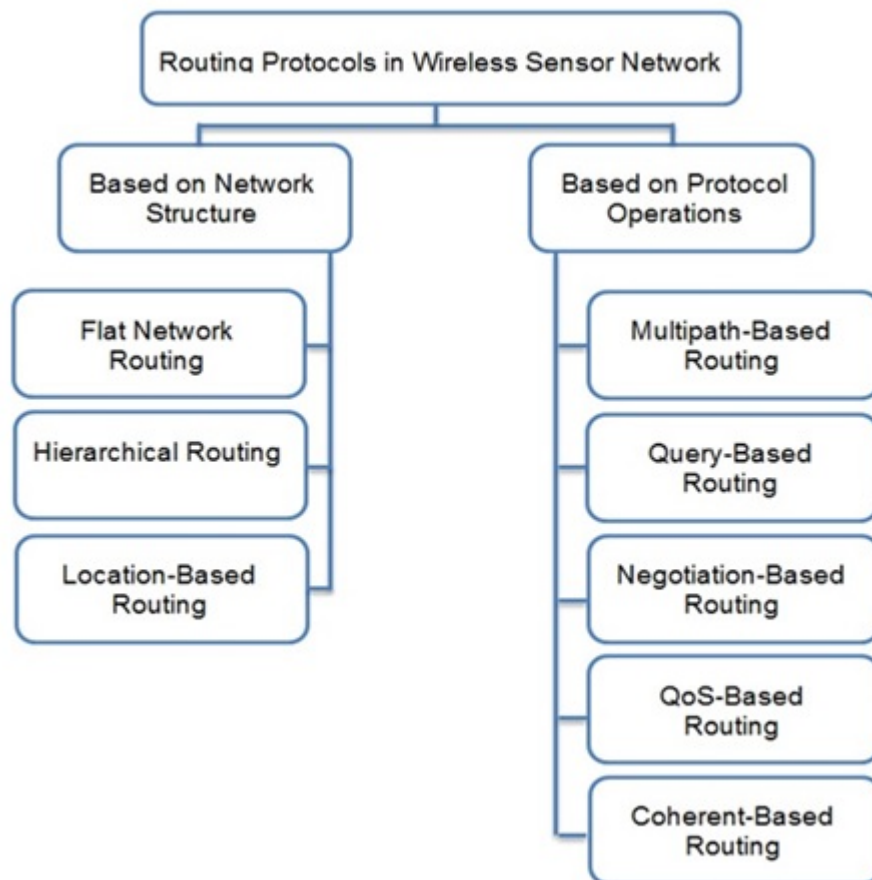
Figure 2.6. Classification of routing protocols in WSNs.

from the nodes by flooding the network with route request packets. Hybrid routing protocols are a combination of both proactive and reactive protocols [83]. In WSNs, in the case of static nodes, the proactive (table-driven) routing protocols are considered the most suitable, as they use less energy than reactive (on demand) routing protocols [84].

Alternatively, the authors in [85] categorised routing protocols based on the network structure or on protocol operation, and this classification is depicted in Figure 2.6. Based on the network structure, routing protocols can be classified into flat routing, hierarchical routing, and location-based routing protocols [20, 38]. In relation to the protocol operations, there are five sub-categories: query-based, negotiation-based, multipath-based, QoS-based, and coherent-based routing [85].

2.5.1 Based on Network Structure

Flat network routing: In the flat-based routing protocol, all the SNs play an equal role, but it is impossible to give a global identifier ID to many SNs. This concern has prompted the formation of data-centric routing, in which the key idea is that the BS broadcasts request queries to the whole network to recover data about events, without considering the topology or the structure of the network [82]. Each node that
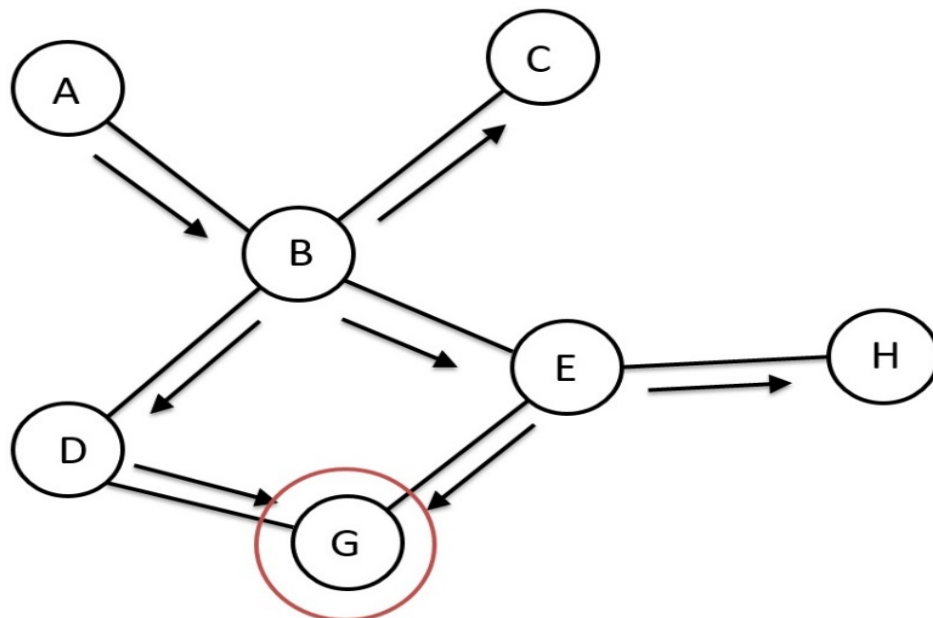
Figure 2.7. Flooding protocol with overlapping problem.

receives the request will repeat the same process of broadcasting, as shown in Figure 2.6. The flooding technique is generally used in this category to transfer the data through the network.

However, flat routing protocols have some critical issues. One of the issues is the duplication of data when the same message is sent more than once to the same node. Another problem is the possible overlapping that can take place when several SNs in the same area transmit the same data to the same neighbour. This is demonstrated in Figure 2.7. where Node G indicates the overlapping problem [86]. The latest work under the umbrella of the flooding technique is directed diffusion [27], SPIN [24], and rumour routing [87].

Hierarchical cluster routing: The core idea of the hierarchal routing protocols is to subdivide the WSNs into a group of nodes called clusters in levels, and each cluster is coordinated by an elected leader node named the CH, as demonstrated in Figure 2.8. The node with the greatest amount of energy can process and transmit the information, and the nodes with the lowest-energy can carry out the sensing in the closeness of the target. Hierarchical routing is a resourceful method to reduce the total transmission power and increase the manageability and scalability of the
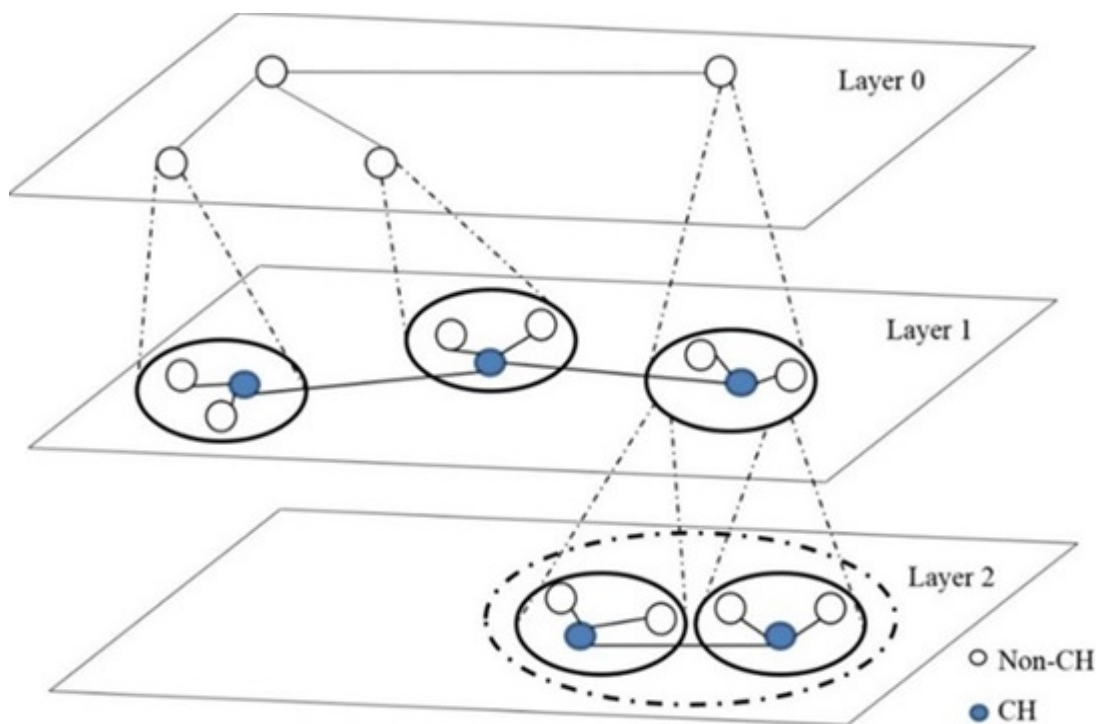
Figure 2.8. Example of hierarchical network.

network. A variety of hierarchical routing protocols have been introduced in this category, including Low-Energy Adaptive Clustering Hierarchy (LEACH) [88], Hybrid Energy-Efficient Distributed (HEED) [89], and Energy Efficient Cluster Scheme EECS [90].

Location-based routing: The main concept of location-based routing is based on the idea that each SN can estimate the distance between their location and the neighbouring nodes within transmission ranges based on incoming signal strength. The physical location of each SN can be directly ascertained if the nodes are fitted with a low-power GPS receiver connected to a satellite. To reduce energy consumption in location-based schemes, the sensor field is divided into equal virtual grid zones, as shown in Figure 2.9.
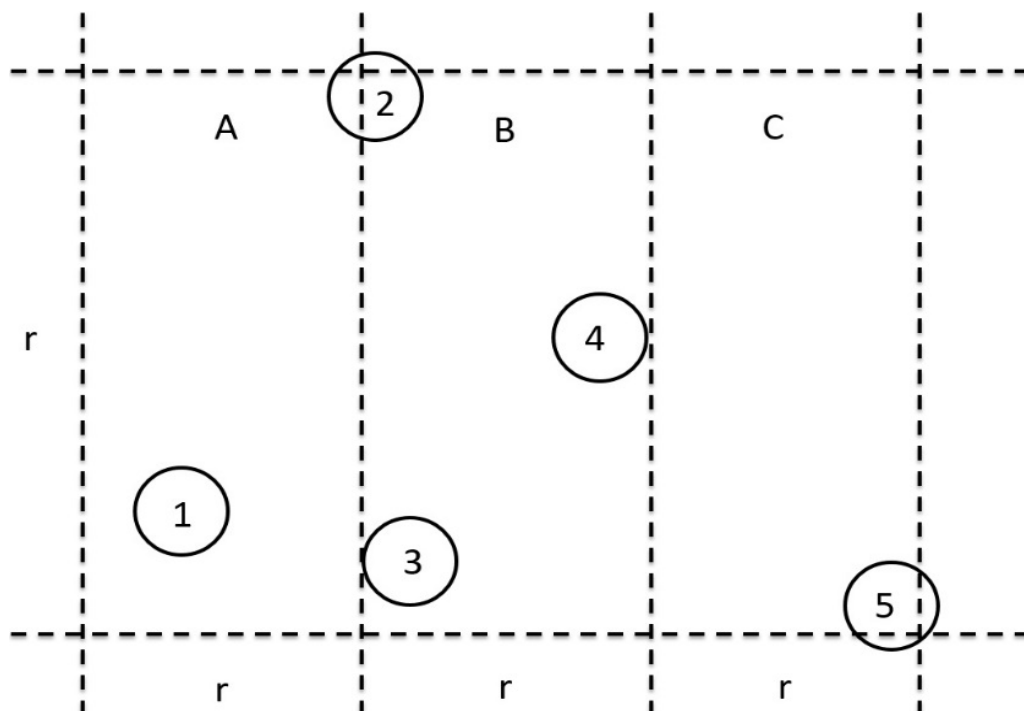
Figure 2.9. Virtual grid zones in GAF.

SNs in the same zone will have equal costs of routing. Therefore, some SN within the same zone can be avoided by putting them into sleep mode. Thus, the more nodes there are in sleep mode, the more energy is saved. Well-known location-based

schemes include geographic adaptive fidelity (GAF) [91] and geographic and energy-aware routing (GEAR) [92].

2.5.2   Based on Protocol Operations

The WSN routing protocols have other classifications based on specific system factors, which can be managed to adjust to existing network conditions and remaining level of energy. These protocols might be divided into the following categories: multipath-based, query-based, negotiation-based, QoS-based, and coherent-based protocols [85].

Multipath-based: Multipath routing protocols improve network performance by using multiple paths routing instead of single path routing. There is always an alternative path between the source and destination as an alternative in circumstance of the primary path failing. Retaining alternative paths would increase network reliability, while also increasing overheads. Directed diffusion is an example of this form of routing protocol [27].

Query-based: In this routing type, the BS sends queries to nodes in the network. The node that is detecting and gathering data matches the data to that requested in the query and transfers the data back to the requesting node or to the BS. The Active Query Forwarded in Sensor Networks (ACQUIRE) is a form of the query routing protocol [93].

Negotiation-based: The negotiation-based protocol uses high-level descriptors for data usage in such a way as to eliminate redundant data transmissions through nodes. In the flooding method, the same data content is sent or exchanged many times between the same nodes, and this causes the reception of duplicate copies of data by SNs. Hence, overlapping and collisions happen during transmissions, where a great deal of energy is consumed during the process. The primary purpose of negotiation-based routing protocols is to prevent duplicate information being forwarded to the next nodes or the BS, by using a sequence of negotiation messages before transmitting the data [24]. The SPIN family of protocols are types of negotiation-based routing protocols.

Quality of service (QoS)-based: The main concept in this type of routing protocol is that the network must balance energy consumption and QoS. Whenever the BS requests data from the SNs in the network, the communication needs to satisfy QoS requirements, such as delay, energy consumption, and bandwidth [85]. The SAR introduced in [25] is the earliest WSN routing protocol to present the concept of QoS in routing decisions. The SAR routing choice is subject to three metrics, specifically, amount of the residual energy, QoS on each path, and priority level of each packet to prevent a path breakdown within the network. Stateless Protocol for End- to -End Delay (SPEED) is another model of this type of protocol [94], which guarantees real-time and end-to-end data transmission. In addition, SPEED obliges each SN to retain data regarding its neighbours and uses geographic forwarding to determine the route.

Coherent and non-coherent-based: Data processing is the main task in the of WSNs process. Routing protocols employ different data processing techniques during the collection and transmission of the data within the network. This type of protocols can be divided into two types of data processing techniques; coherent and non-coherent [20]. In coherent routing, the data is forwarded to aggregators after minimum processing. The minimum processing typically includes tasks like timestamping and duplicate suppression. In order to achieve energy-efficient routing coherent processing is normally selected. In non-coherent data processing routing, nodes will locally process the raw data before sending it to other SNs for further processing. SNs that complete further processing are named aggregators SN or CH. Single Winner Election (SWE) is an example of the non-coherent and Multiple Winners Election (MWE) protocols are an example of a coherent processing [95]. In SWE, the selection of the CH is based on the computational capability and the energy reserves. By the end of the selection process, a minimum-hop spanning tree will be formed to cover the network. In MWE, a simple extension to SWE is proposed. When all SNs send their data to the CH , a large amount of energy will be consumed. Therefore, this process has a high cost. One way to lower the energy cost is to limit the number of SNs that can send data to the CH. At the end of the MWE process, each SN in the network has a set of minimum-energy paths to each CH. MWE process has longer delay, higher overhead, and lower scalability than that for non-coherent processing networks.

2.6   Summary

This chapter outlined the main concepts and theories related to WSNs. It provided a general overview of wireless technology and wireless network classifications, SN structure, and the advantages of using WSNs in some applications. The main routing protocol techniques used to address strict energy saving requirements in WSNs in the transfer of information between SNs were also presented.

WSNs have restricted power and processing competencies and are prompt to breakdown. This breakdown leads to communication interruption and unwanted, common network topology changes. Therefore, it is challenging to design an energy-efficient communication protocol for this kind of network.

Although several communication protocols have been proposed in WSNs, such protocols are still unable to effectively support WSN applications. Hierarchical cluster-based protocols have been regarded by researchers as the most effective and efficient schemes for WSNs to date due to numerous advantages. This efficiency rests in the cluster formation subject to the energy resource of sensors and the sensor proximity to the CH. In the next chapter, we will look at the hierarchical clustering approach in more detail.

Chapter 3

Clustering Technique

T his chapter starts with a general overview of the literature related to the clustering technique and the main advantages of this technique. Furthermore, the aspects necessary to consider when designing a cluster-based algorithm are presented and examined alongside the existing clustering protocols in WSNs. The chapter concludes with a discussion on the gap found in cluster-based protocols, which consequently initiated the aim of this research.

3.1   Concept of Clustering Routing Techniques

As mentioned in the previous chapter, some of the critical issues in WSNs, specifically reduce the energy consumption of the SNs and extend the network lifetime, can be resolved by designing cluster-based routing protocols.

Cluster-based routing protocols significantly enhance the energy efficiency, scalability of the network and lifetime longevity. Cluster-based protocols are constructed by dividing the sensing field into several administrative units termed clusters [96]. The structure imposed by clustering makes it easier to address the problems created by the complexity of large-scale sensor networks. These networks consist of homogeneous, static nodes that all generate data at the same rate. The WSN structure identifies the clustering technique as a crucial part of the organisational structure as illustrated in Figure 3.1. [97].
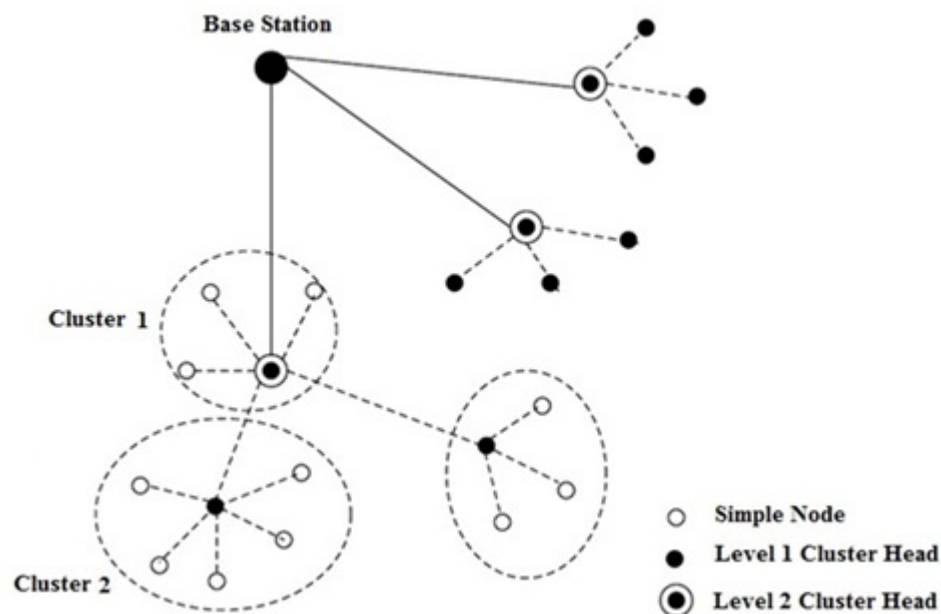
Figure 3.1. Cluster-based model [97].

As soon as the WSN has been distributed into clusters, the communication between nodes can start.   There are two types of communication in clustering-based protocols: intra-cluster and inter-cluster [98]. In intra-cluster communication, the transmission of the packets is among the participating nodes and the CH. However, inter-cluster communication includes the transmission of packets among the CHs or

between the CHs and the BS. Since the CH is the only node able to communicate outside the cluster, collisions between the nodes are avoided, as the nodes do not have to share communication channels with the nodes in other clusters. Thus, this structure and communication pattern helps to reduce energy consumption and latency. It also gives cluster-based protocols different advantages, which are discussed in detail in the following section.

3.2   Advantages of Clustering

The advantages and design challenges of clustering routing protocols can be summarised as follows.

3.2.1   Scalability

In cluster-based routing schemes in WSNs, SNs are subdivided into clusters with different task levels. The SNs within the cluster oversee events, sense and collect data from the surround environment. The CHs role is to aggregate data manage the network. In the cluster topology, the route is formed within the cluster, therefore reducing the routing table size stored within each SN. Compared with a flat topology, cluster-based topology is more flexible in reacting to the network changes and easier to manage. Therefore, cluster-based protocols are better suited to respond to the events in the large networks. [99].

3.2.2   Less Energy Consumption

The data aggregation method in cluster-based routing schemes helps to save more energy by dramatically reducing transmission data. Furthermore, the communication in intra-cluster and inter-cluster can decrease the amount of SNs carrying the communication tasks within the network. In addition, in the cluster-based routing scheme only the CH nodes carry out the task of information transmission, thus lowering the energy consumption of the entire network [100].

3.2.3   Fault Tolerance

This is one of the most challenging aspect of WSN design. The fault tolerance of CHs is essential in the WSN to maintain network functionality and prevent the loss of important information from SNs. Therefore, effective fault-tolerant techniques

need to be considered when designing WSN protocols. Re-clustering, alternative CHs, and CH backup are all viable schemes to managed a CH failure [100].

3.2.4   Load Balancing

Load balancing is a common approach used for extending the network lifetime in WSNs. Clustering distribution technique is an example of a load-balancing approach, typically used for cluster formation, where CHs manage processing of the data and intra-cluster communication [101]. Generally, rotating the CH task equally among the SNs increases the network lifetime since this process avoids the premature energy exhaustion of a single CH. Multipath routing is another technique used to achieve load balancing.

3.2.5   Lifetime Extension

Network lifetime must be taken into consideration in WSN design, as SNs are powered by batteries with limited processing and limited transmission bandwidth, particularly in applications within severe environments. By selecting SNs that is close to most of the SNs in the cluster as a CH, the consumption of the energy during intra-cluster communication can be minimised. In addition, selecting the routes with greater energy resources in inter-cluster communication will consequently lead to greater energy conservation and prolong network lifetime [101].

Although clustering-based schemes have many advantages over flat schemes, especially in relation to energy efficiency, they also have many drawback and various aspects need to be considered when designing clustering-based protocols. These aspects are discussed in further detail in the subsequent section.

3.3   Aspects Considered in Designing a Cluster-based Algorithm

3.3.1   Clustering Formation and Communication

Clustering formation is initiated rounds. Each round is composed of two phases: a setup phase and steady phase [102]. In the setup phase, the CH is elected. After selection, the CHs will start advertising messages to the neighbouring nodes within the radio signal range, and the nodes that receive the messages will send back a join message to the optimum CH and form the cluster. The process is illustrated in Figure

3.2.

In the steady-state phase, the communication process takes place. As demonstrated in Section 3.1, there are two types of communication in the cluster-based scheme [98]: intra-cluster and inter-cluster communication. Intra-cluster communication refers to the communication within the cluster, where each CM node transmits data to a CH. The CH nodes aggregate the gathered data from the CM nodes to avoid duplicated transmissions to the BS.
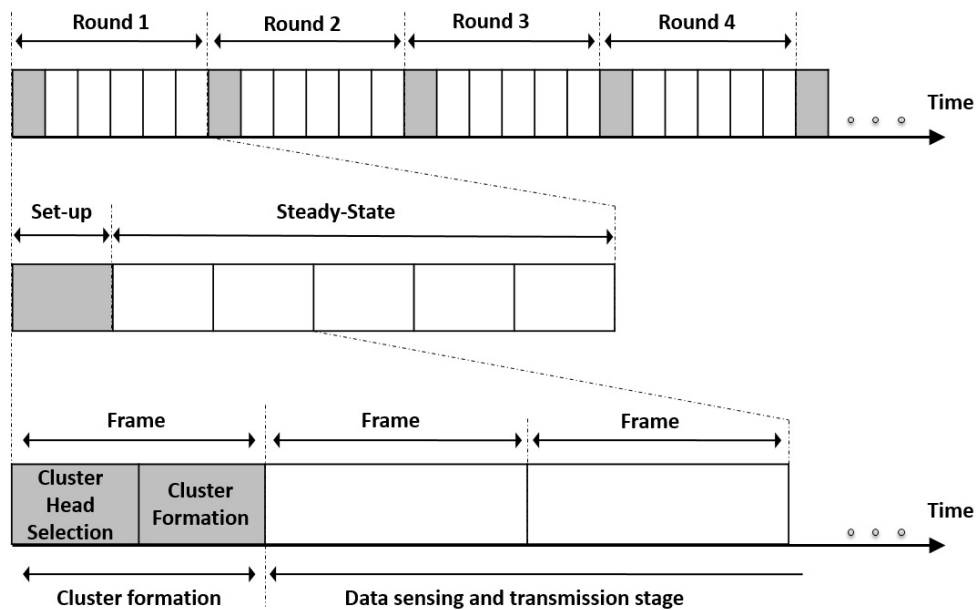
Figure 3.2. Clustering process timeline.

Inter-cluster refers to the transition of data between the CHs and the BS. If the CHs do not have long-haul communication capabilities, clustering algorithms must determine the path between each of the CHs and the BS.

3.3.2   Clustering Method

There are three basic methods for the organisation of the entire clustering formation: centralised, distributed, and hybrid. In centralised clustering, one or more manager nodes are used to divide the whole network and manage the clustering process. Groups of several nodes in the clusters select the CHs. In distributed clustering, each SN can take the decision to become a CH and can form a cluster by running its own algorithm. Hybrid clustering uses both centralised and distributed clustering methods

in its clustering process [97, 103].

3.3.3 Cluster Head Functions

The CH nodes play a significant role in network formation, such as data gathering and data transfer over the network. In such networks, the CH nodes deplete their energy faster than other CMs due to the extra tasks during the network process. Therefore, the CH selection is an important task in cluster-based networks. The CH tasks are not limited to the cluster itself. It is also responsible for the communication among the CHs within the whole network [104]. The main CH functions are as follows.

Data aggregation: In general, the CM nodes remain in sleep mode for long time with radios powered down. Based on the Time Division Multiple Access (TDMA) MAC protocol the nodes become active at multiple times in order to gather the useful information from the physical environment and send it to the corresponding CH at fixed-time intervals [88]. The CH aggregates this information in the same cluster and transmits them to the BS either by one hop or multi-hops by selecting the best next hop.

Data routing: In the hierarchical topology, the CH nodes work as a router. They receive data from the lower level CHs and forward it to the best upper-level CHs [96]. Additionally, the CHs are responsible for forming the backbone of the network by maintaining routing tables.

Topology maintenance: The CH nodes are working with the BS to manage and organise the network. The CHs can provide necessary information to make effective decisions for reforming the clusters and network parameters [96].

The roles of the CHs require extra energy; thus, the CH nodes run out of energy faster than the CMs. Therefore, the CHs no longer capable of processing their tasks need to change or rotate its assigned task after a predefined period.

3.3.4 Cluster Head Rotation

Several CH rotation techniques were proposed in contemporary research literature. Such techniques could be categorised into two main types: time-driven methods and

energy-driven methods [105]. However, repeating the clustering process of the whole network can affect the network performance.

Time-driven rotation: The new CH node election starts on a fixed time in each round by rotating the CH task periodically among the SNs to guarantee the balanced energy consumption of networks [88].

Energy-driven rotation: The CH election and the rotation process started only if the remaining energy of at least one CH has dropped below a dynamic threshold. Using this method, it can easily reduce the effect of the CH rotation and achieve high energy efficiency in the clustering topology [103].

3.3.5   Cluster Head Selection Strategies

From the large number of deployed nodes, the CH can be selected based on probabilistic or entirely random approach or grounded on other more specific conditions [106], as described below.

Probability based: In completely probabilistic schemes, the decision of the nodes to become CH is made without any central authority. In each round, the CHs are elected based on a fixed parameter, such as the number of CHs, current round number, time interval, or node ID [107]. The clustering algorithms based on this classification commonly leads to faster process or convergence times and reduces the number of exchanged messages [108].

Non-probability based: In non-probabilistic clustering algorithm schemes, more attention is paid to specific criteria for selection of CH and formation of the cluster, such as the SN position, proximity, location, connectivity and degree. The selection also depends on the type of data transmitted from neighbouring nodes. Non-probabilistic algorithms generally require a greater number of message exchanges and a greater number of graph traversal, thus generally leading to time complexity in comparison with probabilistic and random clustering algorithms. Alternatively, these types of algorithms are generally more consistent in extracting well-balanced and robust clusters. Combination of metrics, such as transmission power, mobility and remaining energy might also be used in some algorithms in order to achieve more

generalised tasks than single-criterion protocols [108].

3.4   Existing Cluster-based Routing Protocols

Numerous ways exist to differentiate and categorise the clustering protocols in WSNs. The following are the better-known categories of cluster formation principles and factors employed for CH selection.

3.4.1   Probabilistic (Random or Hybrid) Clustering Algorithms

In the probabilistic selection clustering algorithm category, the core objective is to extend the lifetime of the network and scalability and reduce and evenly distribute the consumption of the energy. In this category, LEACH, energy-efficient hierarchical clustering (EEHC), HEED, and their extensions are the best-known protocols. The following section presents the probabilistic clustering protocols in more detail.

Heinzelman et al. [88] proposed the first well-known clustering protocol low-energy adaptive clustering hierarchy (LEACH), which addressed the specific needs of WSNs, including extending the lifetime of WSNs and decreasing the energy consumption of the SNs. The LEACH protocol is a hierarchical, probabilistic, distributed, single-hop protocol. LEACH builds the clusters based on the Received Signal Strength Indicator (RSSI) [88]. Moreover, the CH nodes in the LEACH function as routers to the BS. All the information gathering, such as data fusion and aggregation, occurs within the cluster [108].

Furthermore, LEACH is a distributed protocol where nodes perform independent decisions without a centralised mechanism [88]. Each node has an equal opportunity to become CH, which balances the energy consumption of each SN per round. First, a node decides to be a CH by generating a random number between 0 and 1 and comparing it with a threshold value $T(n)$, expressed by Equation 3.1. The nodes with a random number lower than $T(n)$ will become CHs. Each designated CH broadcasts a hello message to the non-CHs to form a cluster. A non-CH joins the CH that can be reached using the minimum communication energy [88].

$$T(n) = \frac{P}{1 - P[r * mod(1/P)]} \; if \; n \in G, \qquad\qquad 3.1$$

where n is the given node, p is the probability, r is the current round, G is the set of nodes that were not cluster heads in the previous round, *T(n)* is the Threshold.

Generally, LEACH provides a good model of energy consumption, as it provides SNs an equal opportunity to be elected as a CH. When chosen as a CH, an SN cannot become a CH in a following round. Furthermore, LEACH prevents unnecessary collisions from CHs because it uses the TDMA protocols [88]. However, despite its generally energy-efficient performance, LEACH also has some strong drawbacks. For example, LEACH uses a single-hop communication; therefore, it is not appropriate to be used in large-scale networks. In addition, as CHs are elected based on probability, there is a risk that the selected CHs are accumulated in one area of the network. Consequently, some nodes may not have any CHs in their neighbourhood. Figure 3.3 shows the basic topology of LEACH.
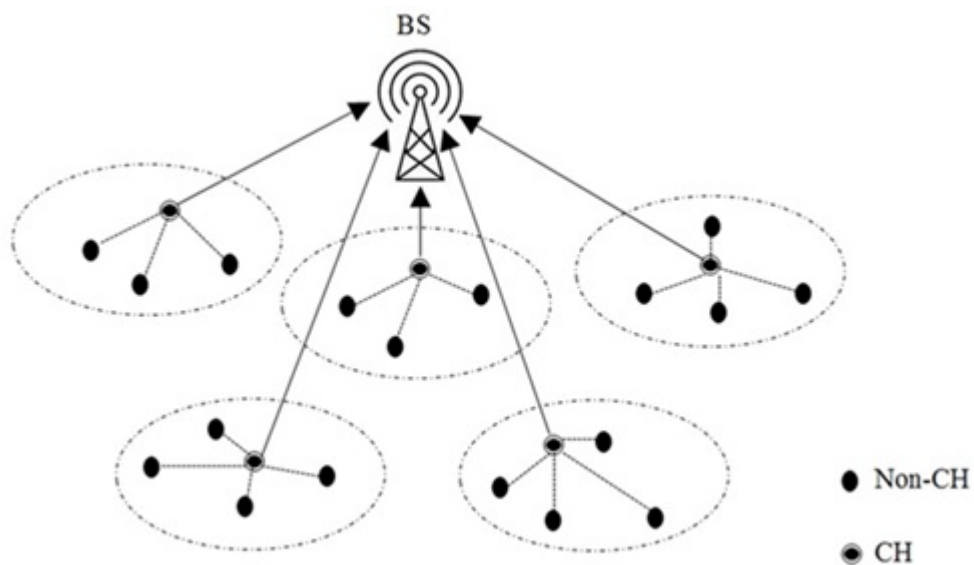
Figure 3.3. Basic topology of LEACH [66].

To address the shortcomings of LEACH regarding CH location and number, a centralised form of LEACH called LEACH-centralised (LEACH-C) was proposed by Heinzelman et al. [109]. In this protocol, the BS decides which SNs become CHs and creates a cluster. Each node passes on information regarding its position and

level of energy level to the BS. Once receiving this information, the BS determines the average energy level of the network and rejects nodes with residual energy levels lower than the average for selection as CHs for this particular round. The centralised protocol guarantees that the energy load is equally distributed among all nodes by choosing a predefined number of CHs and distributing the network into optimal equally sized clusters [109]. Nevertheless, the formation of clusters with an equal quantity of nodes in each cluster is not assured in this protocol because some nodes that are far from the BS might not be able to send information on their status.

Another important probabilistic clustering algorithm offered by Kumar et al. [110] is energy-efficient hierarchical clustering (EEHC). The authors of this protocol are addressing the shortcomings of the LEACH protocol including the one-hop random selection algorithm. The EEHC protocol extend the network multi-level clustering structure by repeating the process of the clustering at the level of CHs, thus allowing multiple levels of cluster hierarchy. The EEHC protocol consists of two phases: initial and extended. In the initial stage, each SN sends a hallo message with probability p to the neighbouring SNs within its communication range inviting them to become CHs. These CHs are called volunteer CHs. Nodes that are located within a k hops coverage of a CH acquire this hallo message either by direct communication or through forwarding. The nodes that receive the message and are not a CH become members of the closest cluster [110]. The second stage, called extended stage, concerns building multi-levels within the cluster hierarchy. The protocol guarantees multi-hop connectivity between CHs and the BS. In an inter-cluster communication, this protocol ensures that the energy consumption by CHs that are located far from the BS is decreased because these CHs do not have to communicate directly with the BS. Furthermore, the authors of this algorithm show the worth of using multiple levels of cluster hierarchy by proving that the consumption of the energy within the network is considerably minimised. However, the weakness of the EEHC rests in the fact that the nodes close to the BS use up more energy compare to the rest of the nodes in the network, which causes an energy-hole problem.

Hybrid Energy-Efficient Distributed (HEED) clustering was introduced by Younis et al. [89]. The authors improved the LEACH protocol using two basic

parameters to select the CHs. The first parameter is the remaining energy of each node, and the second parameter is the intra-cluster communication cost as a task of cluster density or node degree calculated by Equation 3.2. In HEED, the CH nodes are elected systematically, different from the LEACH protocol. Only SNs that contain more of the remaining energy have the chance to be elected as CH nodes. Additionally, there is a little chance that two nodes within the communication range would become CHs [111]. When comparing the LEACH protocol to the HEED protocol, the CH nodes are well distributed throughout the sensor field in HEED. Yet, HEED is not able to fix the cluster number in each round and the energy consumption is not balanced because more CHs are produced than the estimated number, and it also creates massive overheads because of the multiple rounds.

$$CH_{prob} = C_{prob} \frac{E_{residual}}{E_{\max}}, \qquad\qquad 3.2$$

where C_{prob} is set to assume that an optimal percentage cannot be computed a priori, $E_{residual}$ is the estimated current energy of the node, and E_{max} is a reference maximum energy.

Li Qing et al. [112] introduced a distributed multi-level clustering algorithm for heterogeneous WSN (DEEC) to expand upon HEED. In DEEC, the CHs are chosen by a probability, based on two basic stages. First, each node calculates its residual energy ratio at a particular round and uses it as the reference energy. The second stage calculates the optimum number of CHs on the basis of the reference energy and its own remaining energy. The authors of this protocol presumed that the nodes have diverse amount of energy. With these adaptive values, the SNs decide probabilistically on their role in each round. The main drawback of the DEEC is that each node requires a global knowledge of the network, which raises the overheads.

Ever et al. [113] introduced an unequal version of HEED (UHEED). While HEED defines equal sized clusters. The closest clusters to the BS have smaller sizes compared to those farther away. Therefore, the amount of intra-cluster traffic is significantly reduced, and the nearest SNs to the BS consume less energy than distant SNs. Although UHEED improves the performance of HEED, the network lifetime can still be improved further. Energy consumption can be saved by reducing

the cluster-reforming process [114].

Mardini et al. [115] introduced a rotate version of HEED (R-HEED). With this protocol, the authors improved the performance of HEED by applying a different inter-cluster approach. The new approach conducts the clustering process based on certain rules. At the start of the setup phase of each round, the CH node must delay waiting for a period for a cluster reformation message coming from the BS. If the cluster reformation message is not received, each cluster perseveres, rotating the CH task within the same cluster. However, R-HEED does not consider energy consumption in randomly rotating the CH [114].

Aierken et al. [116] proposed a new protocol called RUHEED to improve UHEED performances and increase the network lifetime. The RUHEED protocol is composed of three phases: CH selection, cluster formation, and rotation. In the CH selection phase, the HEED algorithm is used. During the cluster formation phase, the competition radius formula defined in EEUC is used. In the rotation phase, the CH elects one of its CMs as the new CH without performing any election process. The node with the highest residual energy will be the first candidate to become a CH for the next round. The rotation phase is performed until one of the nodes completely depletes its energy. At this stage, the BS will inform all the nodes to perform a new CH election process, and the cluster formation phase restarts again. Although RUHEED improves the performances of UHEED, more energy can be saved if a dynamic CH rotation mechanism is introduced. More precisely, the setup phase can be replaced by developing a new rotation process. When the current CHs residual energy goes below a specific threshold, it will trigger a new cluster formation phase [114].

In conclusion, the probabilistic protocols can be considered a prominent type of clustering protocols in WSNs mainly because of the simplicity of the protocols and their capability of reducing the energy consumption. Simple protocols, such as the ones covered above, introduced different techniques with marginal complexity time and ability to enhanced energy efficiency. Additional probabilistic protocols have been proposed, such as EEMC [117], EECS [90], MOCA [118], TCCA [119], and RECA [120], which have shown significant improvements in relation to balanced

energy consumption and prolonging lifetime of the WSNs. However, the simple drawback of these protocols is their probabilistic nature, which causes the CHs to not be continually well spread and the CH task is not rotated equally every time. This consequently affects the distribution of energy consumption.

3.4.2   Non-probabilistic Clustering Algorithms

The non-probabilistic selection clustering protocols adopt more explicit principles for CH determination and cluster formation. These are generally centred on SN proximity, position, connectivity, location, and degree. Protocol examples that fall within this category include Hierarchical Control Clustering (HCC), Power-Efficient and Adaptive Clustering Hierarchy (PEACH), and Distributed Weight-Based Energy-Efficient Hierarchical Clustering (DWEHC).

The Hierarchical Control Clustering (HCC) algorithm is particularly convenient for networks comprising a vast number of nodes where scalability is the main concern. In these applications, energy efficiency, data fusion and load balancing are the main routing performance criteria [39]. The HCC protocol can enhance scalability and reduce the energy consumption and is also resourceful in unicast, multicast, and broadcast communication environments. Cluster formation process is triggered when the current CH falls below a quality threshold. The cluster formation is based on a BFS (Breadth First Search) tree, which involves constructing a spanning tree in time proportional to the diameter of the network by doing a distributed breadth-first search. The author assigned a weight value to each node for CH election. The goal of hierarchical control clustering is to form multi-tier hierarchical clustering. In hierarchical control clustering, a cluster is defined as a subset of vertices, whose induced graph is connected. This clustering scheme desires many conditions for each layer of the hierarchy, such as: each cluster is connected, all clusters should have a minimum and maximum size constraint, and a SN in any layer belongs to a constant number of clusters. In this scheme, each SN needs to discover its sub-tree size and each of its children's information in the BFS tree. When a SN notes that its children and the sub-tree sizes have not changed for the last max-consecutive-static-sub-tree it terminates the cluster formation process. The proposed multi-level hierarchy is illustrated in Figure 3.4 [39]. This type of

clustering technique has been recognised to be efficient in dynamic conditions. Nevertheless, this type of network can not be considered as a localised routing protocol since the spanning tree is a global data structure and the entire network needs to be completed before it can be computed.
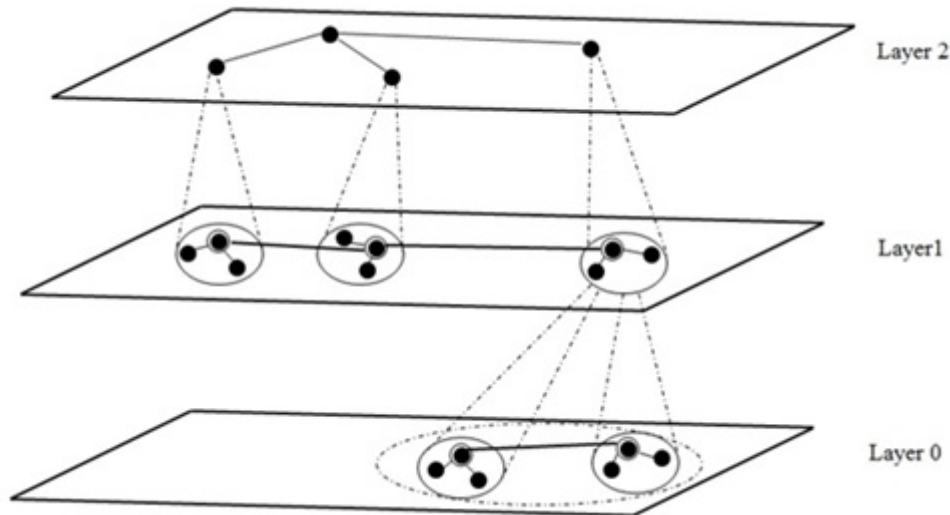
Figure 3.4. Multi-level HCC protocol.

In most of the current clustering protocols the cluster formation overheads and fixed-level clustering consume large amounts of energy, especially when SNs are sparsely installed in the sensor field. To address this challenge, Sangho Yi et al. [122] introduced the Power-Efficient and Adaptive Clustering Hierarchy (PEACH), which aims to minimise the energy consumption of each node and extend the network lifetime. In the PEACH protocol, a node becomes a CH when it receives a packet intended for the node itself. When the packet is intended for a different node, the node that received the packet joins the destination node cluster [39]. The simulation results show that PEACH results in less energy consumption and a higher network lifetime when compared with LEACH and HEED algorithms.

Li et al. [123] proposed an Energy Efficient Unequal Clustering protocol (EEUC), in which the election of CHs is based on the remaining energy of each node and its distance to the BS. To address the hot spot problem, EEUC divides the nodes into unequal-size clusters. The closest clusters to the BS have smaller sizes compared to those farther away from the BS. Thus, the CHs closer to the BS can

save more energy for inter-cluster data forwarding, and the overall energy consumption among CHs is balanced. Compared to LEACH, EEUC uses time-driven CH rotation that may cause a lot of unnecessary waste of energy.

Ding et al. [124] proposed a Distributed Weight-based Energy-efficient Hierarchical Clustering protocol (DWEHC), which has proven to be a development on the HEED protocol. Its core achievement is its significant energy efficiency achieved by improving the intra-cluster topology and creating balanced cluster sizes. After discovering the neighbouring nodes in its surroundings, each SN computes its weight. The node with the largest weight is selected as a CH, and the remaining nodes become child nodes. At this phase, the nodes are regarded as first level members because they have a direct link to the CH [124]. With the child nodes further separated into levels, the total number of levels depends on the cluster range and minimum energy of the CH. Like HEED, DWEHC is a fully distributed clustering protocol but has more balanced CH distribution. Additionally, its clustering process does not rely on network size. Nevertheless, this protocol is not able to increase its energy efficiency because of its inter-cluster communication function and large control message overheads.

3.4.3   Clustering Algorithms for Reactive Networks

All the protocols outlined above are proactive clustering protocols, which are based on the fact that the sensors always have information to transfer and therefore should all be taken in consideration regarding cluster formation. On the other hand, reactive algorithms use queries or particular triggering actions that happen in the WSN.

The Threshold-sensitive Energy-Efficient sensor Network (TEEN) is a hierarchical scheme for reactive networks suggested by Manjeshwar et al. [125], The TEEN is a blend of hierarchical and data-centric approaches, focusing on data aggregation instead of the formation of the cluster, and has a two-tier clustering topology. The TEEN operates on the basis of two thresholds: the hard threshold (HT) and soft threshold (ST). The HT refers to the minimum of data transmission, and the ST specifies the change range of data detected. In TEEN, the nodes transmit their data only when they fall above the HT and change by a given amount (ST). By varying the two thresholds, this protocol significantly reduces the amount of data

transfer. However, the main drawback is that if the threshold is not achieved, the communication among the nodes will terminate. Consequently, without the communication the information might be lost.

To address the shortcomings of TEEN, the Adaptive Periodic-TEEN (APTEEN) protocol was presented by Arati Manjeshwar et al. in [126]. The APTEEN is a hybrid clustering-based routing protocol in which the SNs respond to time-critical events. The nodes must have global knowledge at periodic intervals in an energy-efficient method. The selection of the CH in APTEEN uses a similar mechanism to LEACH-C. The structure of APTEEN is similar to that of TEEN, where both protocols use the concept of hierarchical clustering in the communication among source nodes and the BS in order to achieve higher energy-efficiency. The APTEEN protocol is based on three different queries:

- Historical query to analyse past data values;
- One-time query to take a snapshot view of the network
- Persistent queries to monitor an event for a period.

The main concerns of APTEEN are the overhead accruing during multi-level clusters formation, the technique of applying the threshold functions and the fact that it does not exploit spatial and temporal data connection for efficiency improvements.

Decentralized Reactive Clustering (DRC) was suggested by SH Yoon et al. [127]. Similarly to other reactive algorithms, the clustering procedure is initiated only in the case of events detection. Four different operation phases are defined: the postdeployment phase, followed by a cluster-forming phase, which is when clusters are constructed, then an intracluster data processing phase and finally a CH-to-processing center phase. DRC uses power control technique to minimize energy usage in cluster formation. Unfortunately, simulations only compare DRC against LEACH and therefore do not highlight its performance gains or disadvantages against other reactive clustering protocols.

The Clustered AGgregation (CAG) [128] mechanism was proposed by Yingyue Xu et al. CAG utilizes the spatial correlation of sensory data to further reduce the number of transmissions by providing approximate results to aggregate queries.

CAG guarantees the results to be within a user-specified error-tolerance threshold. Cluster formation is performed while queries are disseminated to the network (query phase), where clusters group nodes sensing similar values. Subsequently, CAG enters the response phase wherein only one aggregated value per cluster is transmitted up the aggregation tree. In effect, CAG is a lossy clustering which trades a lower result precision for a significant energy, storage, computation, and communication saving.

3.5   Conclusion

This chapter discussed the concept of the clustering technique and the main advantages of this technique alongside the aspects necessary to be considered when designing the clustering protocol. This chapter presented an overview of the main characteristics of existing clustering protocols in WSNs to address the issue of energy consumption and prolong the network lifetime, along with the limitations of each protocol and an indication of how researchers have improved on existing structures to address their weaknesses.

It is evident from the literature review that the cluster-based scheme is currently considered the most efficient method to enhance scalability, reduce the total amount of communications, and energy consumption in WSN applications. The current clustering-based protocols presented in the literature review focus on reducing the energy in the steady-state phase at the formation of the cluster and the CH selection, in order to use the rare resources more efficiently and reduced energy consumption. However, in clustering schemes, the CH node takes more responsibility than the CM node, due to acting as a transfer point, such as in intra-cluster data aggregation and long-distance communication to the BS [129]. Therefore, the CH node consumes more energy during the communication process and will quickly run out of energy. That causes a breakdown of the cluster and loss of the communication between CHs [108]. The only way to avoid this situation and extend the network lifetime is to balance the CH election by rotate the CH task equally within the SNs. However, the CH rotation will become gradually more frequent alongside the consumption of remaining energy of the nodes. Consequently, more and more energy and time will be used during the rotation process setup phase of every round rather than data

transmission steady-state phase, which will eventually decrease the energy of the network to zero.

Therefore, this thesis propose that a significant amount of energy might be saved by minimising the number of rotations in the setup phase when selecting the CH. The following chapter presents new solutions for reducing the number of interactive clustering processes to manage energy consumption.

Chapter 4

New Energy-efficient Cluster-based Protocol for Wireless Sensor Networks

4.1 Background and Motivation

Managing the energy consumption in order to expand network performance is one of the most challenging issues in WSN applications design [100]. Although several solutions have been proposed to address this issue, measuring network performance is still challenging. In a large-scale WSN scenario, the SNs that are located further from the BS rely heavily on the efforts of a set of intermediate nodes to transfer their data. Alternatively, the nodes must use high transmission power to forward their data directly to the BS. Whatever approach is adopted, the latency and power consumption of the entire network are usually affected [131]. Using fixed-time

rounds to rotate the CH role can affect network performance. The CH rotation scheme is a cluster topology maintenance mechanism [132]. It plays a key role in restoring, rotating, and reforming the cluster structure to avoid an early death of CH nodes and to prolong the network lifetime [104].

Large number of the routing protocols follow the concept of the LEACH protocol [88]. In such protocols, the life span of the network is divided into number of frequent fixed-time rounds, as Figure 4.1 demonstrates. It has been shown, that applying the fixed round time in the cluster based protocols, leads to unequal distribution of loads [111]. As discussed in Section 3.5, the CH task needs to be rotated among all nodes in the network to enhance the load balance and ensure efficient energy consumption. Thus, all nodes in the network need to start a new CH election process every fixed time. However, given that cluster-based protocols require regular re-clustering for balanced energy consumption, repeating the clustering process of the whole network will increase network overhead and will consequently decrease network operation time.
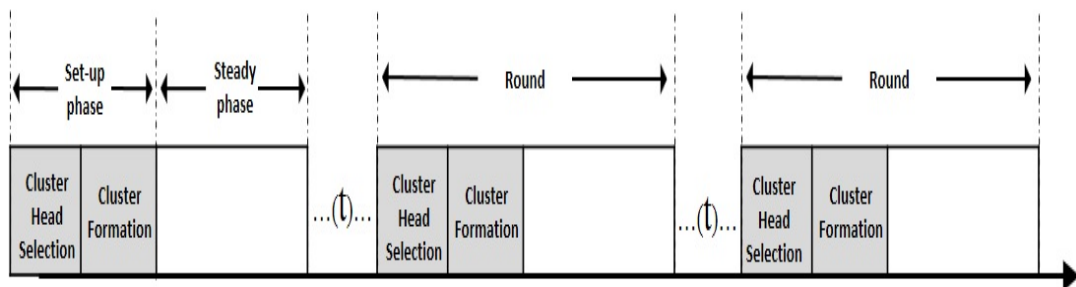
Figure 4.1. LEACH protocol cluster process round.

Therefore, to fill this gap, the objective of this chapter is to prove that modifying the round lengths will lead to greater energy efficiency and enhance the performance of the network. We attempt to design a new cluster-based protocol, referred to as a Load-balancing Cluster Based Protocol (LCP) [133]. The LCP introduces a new inter-cluster approach to reduced energy consumption and increase the network lifetime. This new protocol continuously rotates the election of the CH in each cluster and selects the node with the highest residual energy in each round. Unlike

the R-HEED that rotates the CH election only once within the cluster, LCP keep rotating the CH election until each node within the cluster becomes a CH.

4.2   Proposed Mechanism

The proposed mechanism builds on the success of the HEED protocol [111]. The clustering phase of the HEED protocol has been modified to make it more energy efficient. The HEED protocol is divided into several rounds and each round has two main phases: setup phase and steady phase. However, in the LCP, the setup phase and steady phase are only run in the first round. After the first round, the LCP will maintain the clusters and continue to rotate the leadership among them within the same cluster by selecting the node with the highest energy each round. This delays the frequency of the re-clustering message coming from the BS. Using this mechanism improves energy efficiency by avoiding the overhead control message exchange during the re-clustering process. Figure 4.2 demonstrates the flowchart of the timeline that occurs each round in the LCP.

The LCP is similar to HEED in terms of the following features:

- The elected CHs sent advertisement messages only to one-hop neighbours.

- The network is homogeneous and all SNs have the same initial Energy capacity.

- The cluster formation setup phase finishes in O (1) iterations.

- Each node becomes a member only in one cluster and communicates directly with its CH.

- Through the cluster formation process, nodes can become either a candidate CH (C_{CH}) or a final CH (F_{CH}) or can be covered.

- At the end of the clustering procedure, CH nodes form a network backbone. Thus, the data are forwarded in hop-by-hop through CHs until the arrival at the BS.

- The steady-state phase for the LCP is like HEED, and CH election is done as part of an iterative process.
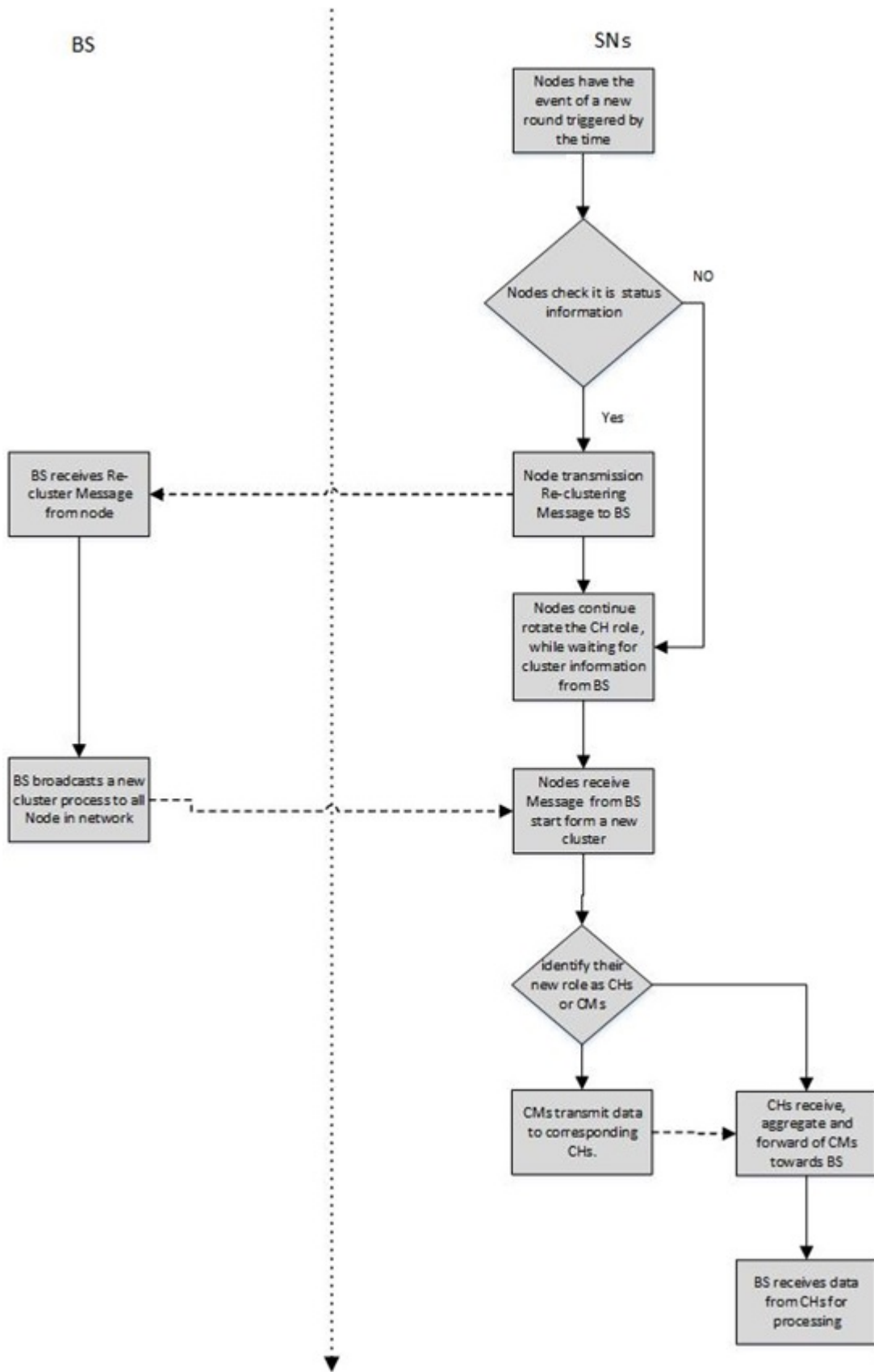
Figure 4.2. LCP clustering process flow chart.

4.3   Implementation

The LCP contains three main stages in the setup phase in the first round: the initialisation, repeat, and finalise stage. In the next round, the CH rotation phase takes place. More details for each stage description are presented below for clearer understanding. Table 4.1 shows the control packets used in LCP.

Table 4.1. LCP control packet parameters.

Message	Description
Candidate_msg	(NodeID, CCH, cost)
Final_msg	(NodeID, FCH, cost)
Join_CH_msg	(NodeID, ResidualEnergy)
Schedule_msg	(Schedule order, Threshold)
Rclust_msg	(NodeID, FCH)

4.3.1   Initialisation Stage

At this stage, same as in HEED, nodes compute their information to define the cost, which is the remaining energy and the node degree. Unlike HEED, the costs in LCP are exchanged through the CH message. The nodes set an initial percentage (CH_{prob}) to become CHs computed according to the proposed Equation 3.2. Each SN establishes its probability of becoming a CH based on the remaining energy, as in HEED. In addition, nodes set the F_{CH} status to false as default values. The pseudocode of the initialisation stage is given in Algorithm 4.1.

```
Algorithm 4.1 Initialisation Stage
1: procedure INITIAL PERCENTAGE OF CHs
2:     for each node  do
3:         set with CH probability ← CH_prob
4:         set with Not CH status F_CH ← false
5:     end for
6: end procedure
```

4.3.2   Repeat Stage

At this stage, each node is subject to a delay time before starting the iteration process, in which it can select its status either to become a C_{CH} or a F_{CH}. The node

decision to become F_{CH} is based on probability CH_{prob}. Any status a node selects, it sends a declaration message *cluster head msg* (node ID, node status, cost), where the selection status is set to F_{CH} if its ($CH_{prob} = 1$), otherwise is set to C_{CH}. Every node within the communication range reserved the *cluster head msg* will add it to an array (S_{CH}). The nodes with the lowest cost in S_{CH} will declare itself a F_{CH}. The pseudocode of the repeat stages is given in Algorithm 4.2.

Algorithm 4.2 Repeat Stage

```
 1: procedure SELECT CANDIDATE CH
 2:     while (CH_previous < 1) do
 3:         if (SET S_CH isNotEmpty()) then
 4:             if MyNode = Lowest Cost(S_CH) then
 5:                 Broadcast Final CH message
 6:                 F_CH ← TRUE
 7:             else
 8:                 if (CH_prob = 1) then
 9:                     Broadcast Final CH message
10:                     F_CH ← true
11:                 else
12:                     Broadcast Candidate message
13:                 end if
14:             end if
15:         else
16:             if Random(0, 1) <= CH_prob then
17:                 Broadcast Candidate message
18:             end if
19:         end if
20:         CH_previous ← CH_prob
21:         CH_prob ← min(CH_prob * 2, 1)
22:     end while
23: end procedure
```

4.3.3 Finalisation Stage

During this stage, most SNs must declare themselves either F_{CH} node or a member node. If a node received a final CH message, it will join the F_{CH} with the lowest cost. If the node is neither F_{CH} nor has received a CH advertise message, it will declare itself a F_{CH} node. The pseudocode of the finalisation stage is given in Algorithm 4.3

Algorithm 4.3 Finalisation Stage

1: **procedure** SELECT FINAL CH
2:     **if** $F_{CH} \leftarrow false$ **then**
3:         **if** (S_{CH} isNotEmpty()) **then**
4:             $MyNode = Lowest\ Cost(S_{CH})$
5:             Join Cluster message
6:         **else**
7:             Broadcast Final CH message
8:         **end if**
9:     **else**
10:         Broadcast Final CH message
11:     **end if**
12: **end procedure**

4.3.4   Rotation Stage

After the F_{CH} has been elected and forms clusters in the first round, each F_{CH} constructs a rotating schedule for its members (S_{Cmber}) when it becomes a CH. The rotating is sorted based on residual energy in the SN. The node with the highest residual energy will be the first candidate to become a CH for the next round. Therefore, at the beginning of the next round, unlike in the HEED protocol, it is not necessary to re-cluster the network. Nodes within the same cluster in subsequent rounds continue rotating the CH role between them by selecting the node with the highest residual energy every round. When the first cluster finishes the rotating process, it informs the BS by sending a re-form cluster message via a multi-hop route. The BS re-broadcasts the message among the nodes to inform them of the start a new cluster process. The re-clustering process is necessary in order to load balance the inter-cluster communication. The pseudocode of the CH rotation phase is given in Algorithm 4.4.

Algorithm 4.4 Rotation Stage

1: **procedure** SELECT CH NEXT ROUND
2:     **if** (SET CM isNotEmpty()) **then**
3:         Select Next node as F_{CH}
4:         Sent Join Cluster message
5:     **end if**
6: **end procedure**

By adopting this technique, we aim to reduce the overhead caused by the clustering process required in every round at the setup phase. Figure 4.3 compares the clustering process timeline between the traditional cluster process and LCP.

In the traditional cluster process, nodes consume more energy due to the re-clustering process (setup phase) as shown in Figure 4.3(a). In comparison, Figure 4.3(b) shows the LCP timeline, which does not include multiple setup phases and therefore consumes less energy.
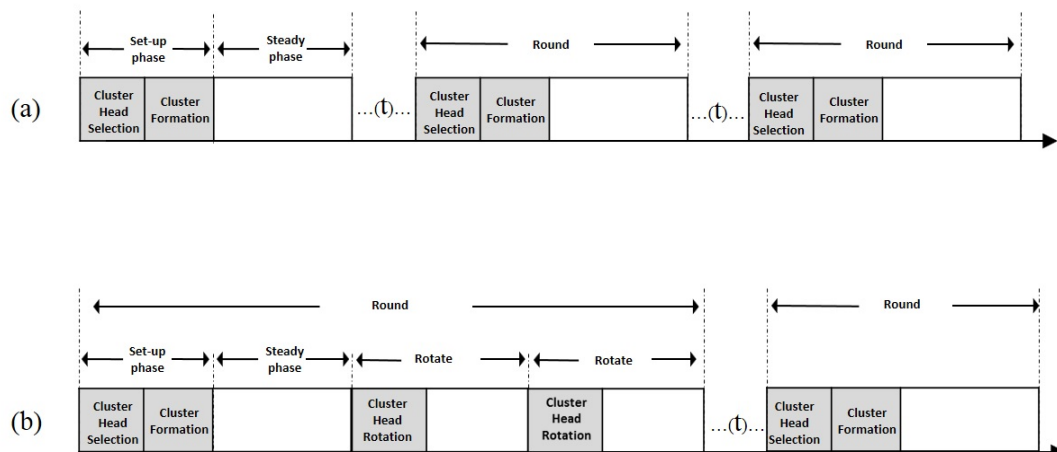
Figure 4.3. Difference timelines between traditional clustering process and LCP.

4.4   Simulation Models

Many networking SNs form WSNs. Therefore, it can be relatively difficult or even impossible to design a WSN analytically and it can also create oversimplification of the analysis with limited confidence [134, 135]. Moreover, installing test-beds carries a huge effort and cost [136, 137]. Additionally, a number of factors influence the simulation results simultaneously, therefore it is difficult to separate a single feature. The methods previously suitable for wired and wireless networks cannot be applied as the characteristics of a WSN force designers to employ different approaches.   Simulation is crucial to examine WSN, as it is a well-known method for testing new applications and protocols in the WSNs [116]. The growing interest in WSNs and the rising number of proposals for new applications has resulted in recent growth of simulation tools available to model WSNs. Simulation software

commonly provides a structure to model and replicate the behaviour of real schemes [134, 136]. Protocols, schemes and concepts can be assessed on a very large scale, and WSN simulators permit users to separate diverse aspects by modifying configurable features. The vibrant advancement in the area of WSNs requires designers to create simulators with rather explicit capabilities. By utilising such simulators, researchers can verify new concepts and test the solutions in a virtual environment, saving time and avoiding large costs of hardware [138].

Several simulation tools exist to implement and study wireless network algorithms. Some of the classical simulation tools that were considered suitable for our protocols include NS-2/3 [139], OPNET [140], OMNeT++ [141], J-Sim [142], and TOSSIM [143]. Although it is not an intention of this section to provide a detailed description of each simulation, the following comparison serves as a justification for our choice of simulation. The choice of simulator was based on the motive of our study, level of complexity, cost, consistency in the results, and level of support offered by the community.

As network simulator, NS-2 has virtually established itself as the standard network simulator suitable for wire and wireless network systems. NS-2 is able to support a substantial variety of protocols in all layers. Additionally, the cost is minimal, because it is an open-source model supported by easily accessible online documents. However, a major shortcoming of NS-2 is its limited scalability [144] in terms of memory usage and simulation runtime. Additionally, as NS-2 is a general network simulator, some distinctive features of WSNs are not taken into account. For example, NS-2 is not equipped enough to examine the bandwidth issue, power consumption and reduction in energy consumption in WSNs. Moreover, the limited time to fully comprehend this complex scripting language and modelling technique was also a factor that influenced our decision.

Similar to NS-2, J-Sim is an open-source model with manual available online. Compared with NS-2, J-Sim is able to evaluate the performance of the network of a larger number of nodes, around 500 [134]. Additionally, J-Sim contains many protocols and is able to support data diffusions, routings, and localisation model [144]. However, the implementation period is longer compared to that of NS-2.

Since this simulator was not initially intended for WSNs, to add new protocols or node features to the fundamental design of J-Sim can be challenging.

A very simple but powerful emulator [137], TOSSIM is similar to NS-2 and J-Sim, and the open-source and online documentation reduces the costs. Additionally, TOSSIM can support large number of nodes, which means it can more precisely replicate real-world conditions. However, TOSSIM is only designed for nodes operations with TinyOS [143], therefore it can not be employed for other protocols. Consequently, TOSSIM is unable to examine the issue of energy consumption in WSNs, which is an essential motive of our study.

The only commercial simulator discussed in this section is OPNET, which is a simulator written in the C++ programming language [144]. OPNET can perform three main functions, modelling, simulating, and analysis. However, OPNET is expensive commercial software, and unlike NS-2 and other simulation tools and likewise TOSSIM, the OPNET model does not support energy models or the simulation of any energy-related aspects of WSNs [137].

The most suitable simulation for our protocol is OMNeT++, which is an excellent simulation software with functions following the requirements of WSN simulation. Compared with NS-2, OMNeT++ has better performance and has some advantages when compared with OPNET [144].

OMNeT++ is open source software intended to simulate the communication networks. Many other research fields, such queuing systems or hardware emulation utilise OMNET++ simulator extensively [145]. Although numerous OMNeT++ based WSN simulation models exists, Castalia [141] has been chosen as the most suitable one for our protocols due to the following reasons. First, Castalia supports networks of low-power embedded devices such as WSNs. Second, it can be utilised to test the distributed algorithms and protocols in realistic radio models and wireless channel. Third, Castalia embraces additional features such as: several popular router protocols and MAC protocols, a model for temporal variation of path loss, and RSSI calculation, which can provide more convincing and accurate simulation results [134].

4.5   Performance Metrics

With more tests carried out in research, more effective resolutions can be achieved. Thus, the lab experiment in this thesis is divided into diverse lab-test scenarios. These scenarios are created for testing basic energy aspects of a WSN used for measuring the temperature in the natural environment. In such a scenario, the SNs are separated in large area. All SNs need to detect the change of the temperature in the sensor field and send all the data to the BS. The BS can be placed either in the exact centre of the sensor field or outside. As the SN is battery-operated, the main concerns are scarce energy sources. Therefore, the most adequate metrics to measure energy consumption are setup message overhead, total energy consumption, and network lifetime. The purpose of these scenarios is to apply the new proposed routing module, along with a varied number of parameters to evaluate the energy performance of the network.

4.5.1   Setup Messages Overhead

This is the cost in regards to the number of control messages exchanged throughout CH election and creating the clusters (setup phase) in every round. The frequent exchanging of setup messages causes more energy waste and influence the network performance [146]. The basic idea behind this proposed method is to avoid unnecessary clustering processes to reduce energy consumption.

4.5.2   Energy Consumption

One of the main goals of the proposed protocol is to reduce the energy consumption of each node, consumed during the communication process. Moreover, in some application the nodes, which are location aware, might consume more energy, the non-location aware nodes. Thus, by calculating the total energy consumed for each the nodes in the network, the energy efficiency of the protocol can be demonstrated. The total energy of the node is calculated by running the experiment for a number of times and then calculating the average of the remaining energy of each node.

4.5.3   Network Lifetime
This metric is calculated using the average energy remaining in all nodes at a specific round. In addition, the network lifetime metric is based on WSN application

requirements. For example, some applications require that all nodes must work to ensure the network has good coverage. Thus, the network lifetime metric for these applications should be measured according to the lifetime of the shortest-living node. Other applications only require a specific percentage of nodes remaining alive to achieve the application requirements [147]. Therefore, the network lifetime in our protocol is measured by following three different metrics [148]. First node dies (FND) is defined as the time elapsed in rounds until the first node has consumed all available energy. Half node dies (HND) is defined as time elapsed in rounds until half of the nodes have consumed all available stored energy. Last node dies (LND) is defined as the time elapsed in rounds until all the nodes have exhausted their entire energy supply. To correctly evaluate the proposed protocol, it is very important to test the scalability along with the network lifetime. In our experiments, we have enlarged the number of SNs from 100 to 350.

4.5.4   Delivered Data Messages

Additional metric for network performance evaluation is the delivered data message. [149]. This represents the quantity of data messages sent from the CHs and received successfully by BS. In the LCP, the link quality and quantity of successful data messages delivered to the BS are not considered. However, the energy efficiency improvements in LCPs should not affect the quantity of data messages delivered to the BS. For that reason, the data messages received at the BS are demonstrated.

4.6   Simulation Scenarios and Results

This section describes the simulation environment to evaluate the performance of the LCP compared to LEACH, HEED, and R-HEED using an open-source Castalia simulator along with the results of the network performance indexes of LCP.

In each simulation scenario, the sensor network composed of (100–350) SNs, which are randomly deployed in a playground of $200\,\text{m} \times 200\,\text{m}$ square region. Each performance metrics is run for thirty seats. All SNs are fixed and homogeneous and with limited stored energy. Nodes are not equipped with GPS-capable antennae. The BS is placed at the centre of the sensor field. The initial energy of each node is 25 J, and the energy consumption is calculated using the data transmission and

aggregation per round. The round time in HEED and LCP is measured in seconds, minutes or hours. In our simulation, we specified a round time of 20 seconds. All data messages have an equal size. In all simulation scenarios, (CC2420) radios are used. Table 4.1 illustrates the overall summary of simulation parameters, network topology, routing protocols, etc.

Table 4.2. LCP protocol simulation parameters.

Parameter	Value
Sensor field	200 m x 200 m
Deployment method	Uniform, random
Simulation time limit	500–1100 seconds
Sensor network number of nodes	100, 150, 200, 250, 300, 350
Initial energy	25 J
Wireless channel-only static nodes	TRUE
Application ID	Throughput test
Sensor node 0 is sink	TRUE
Sink node location	Central
Report destination is sink	TRUE
Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	LPC, LEASH, HEED, R-HEED

Setup messages overhead: Figure 4.4 shows a global comparison between LEACH, HEED, R-HEED, and LCP in terms of the number of messages involved at the setup phase for 100 rounds. It is evident that LCP has the lowest rate of the setup messages due to the reduction of the re-cluster process, which results in lower energy waste and increases the performance of the network. Even when the number of nodes is increased, LCP performs significantly better compared to HEED and LEACH and marginally better compared to R-HEED.
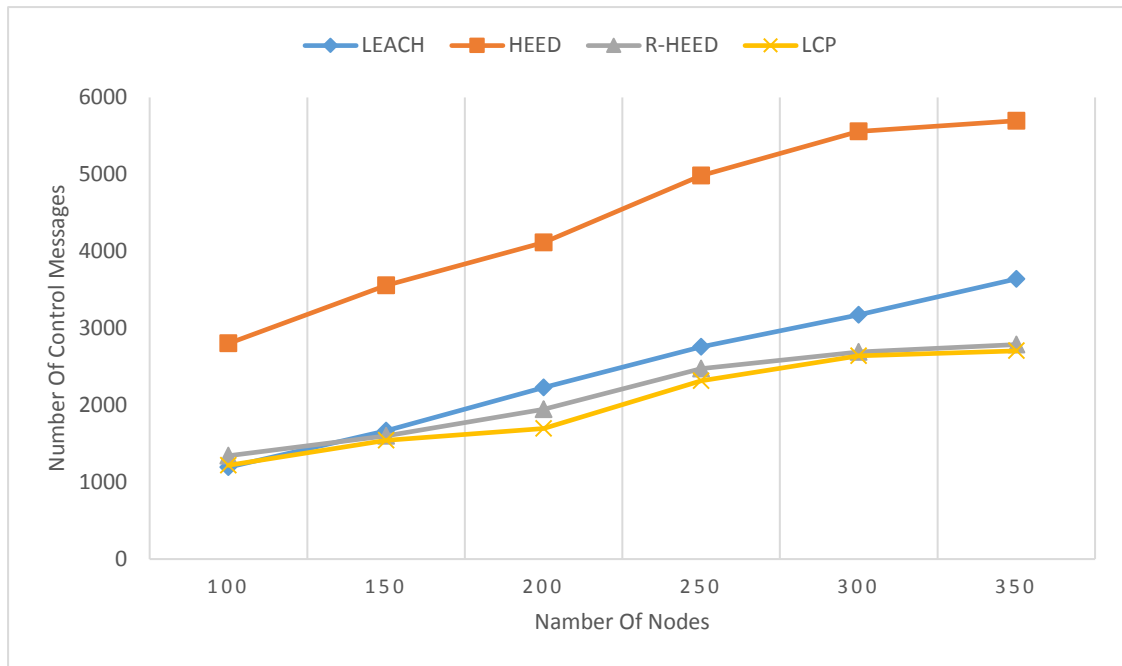
Figure 4.5. Average number of setup messages.

Energy consumption: Figure 4.5 demonstrates the relationship between the remaining energy and number of nodes. It is evident that LCP consumes the least amount of energy. These results show that energy consumption has been reduced by 26.79%, even though the number of nodes are increased. Thus, the LCP has achieved a better performance than it its peers in terms of reducing and distributing power consumption.
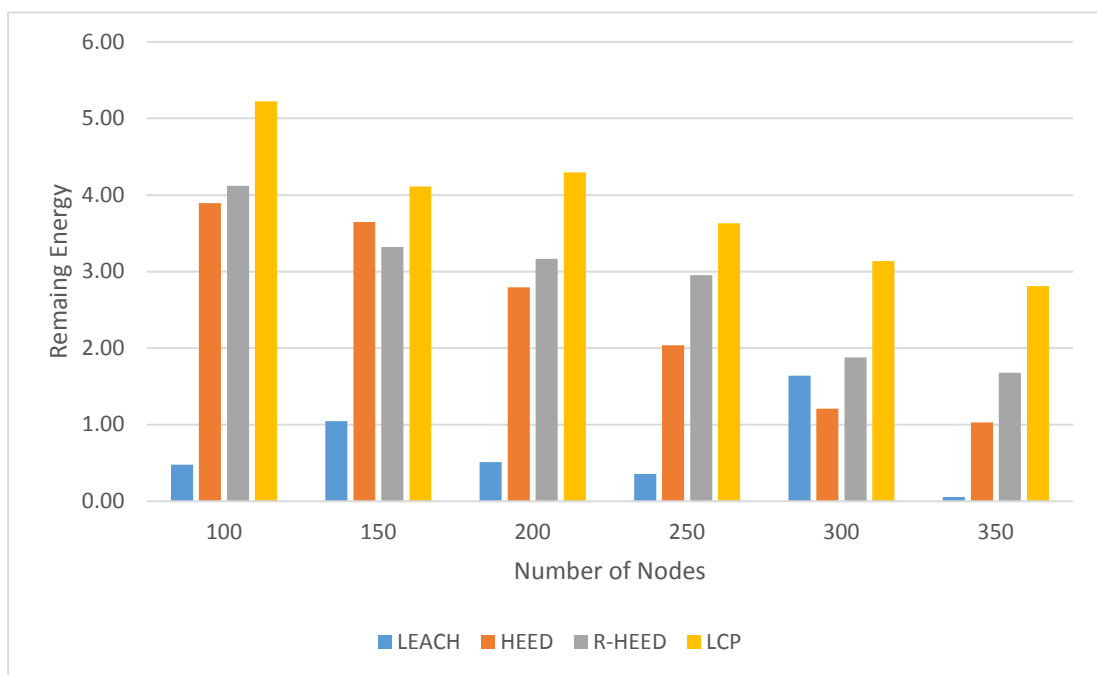
Figure 4.4. Remaining energy in LEACH, HEED, R-HEED and LCP.

Figure 4.6 demonstrates the total number of nodes remaining alive following the simulation round. The LCP increases the network lifetime compared to its peers. We can see that LCP consumes the least amount of energy. The average lifetime in the LEACH protocol was around 800 rounds, while it was around 1000 rounds in the HEED protocol. In R-HEED, the average lifetime as compared to LCP was almost the same at 1100 rounds. This is because R-HEED uses a similar technique without considering the residual energy. Therefore, the new approach of rotating the CH task within the cluster saves more energy by delaying the cluster process.
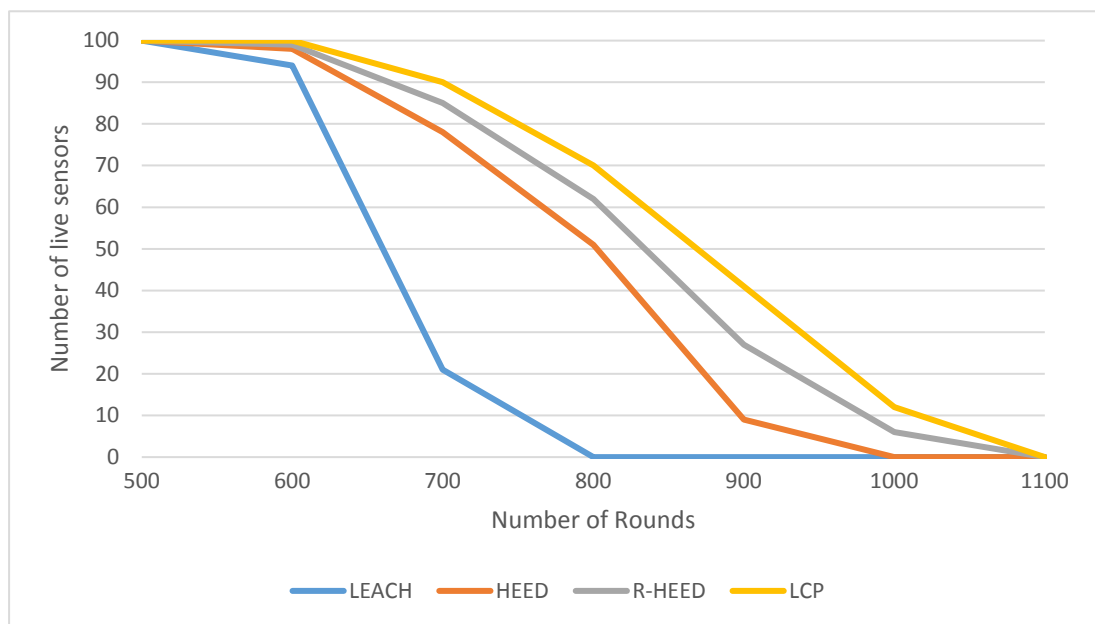
Figure 4.6. Number of live sensors vs numbers of.

Network lifetime: In order to further validate the proposed protocol, similar evaluations are conducted using different lifetime metrics: FND, HND, and LND. The results show how LPC performs better than other protocols even when the number of nodes increases, as Figures 4.7, 4.8, and 4.9 exhibit.

Figures 4.7 shows rounds until the FND in the four protocols examined in the networks of diverse numbers of nodes ranging from 100 to 350. The results show that LCP last longer than the other protocols in FND in all groups of networks. LCP performs best in the 150 node network compared to the other sets. In the networks of 200 and 250 nodes it might seems that LCP performs equally, however error bar demonstrate LCP performs better in networks of 250 nodes by % compare R-HEED.

In the rest of the sets of networks 100, 350 and 300 the LCP performance decreases. In comparison with the other three protocols in their best performance in networks, LCP is more efficient by 3.05% than R-HEED in 200 network size. In addition, LCP is more efficient by 3.64% and 7.87% than HEED and LEACH respectively both in 150 network size.
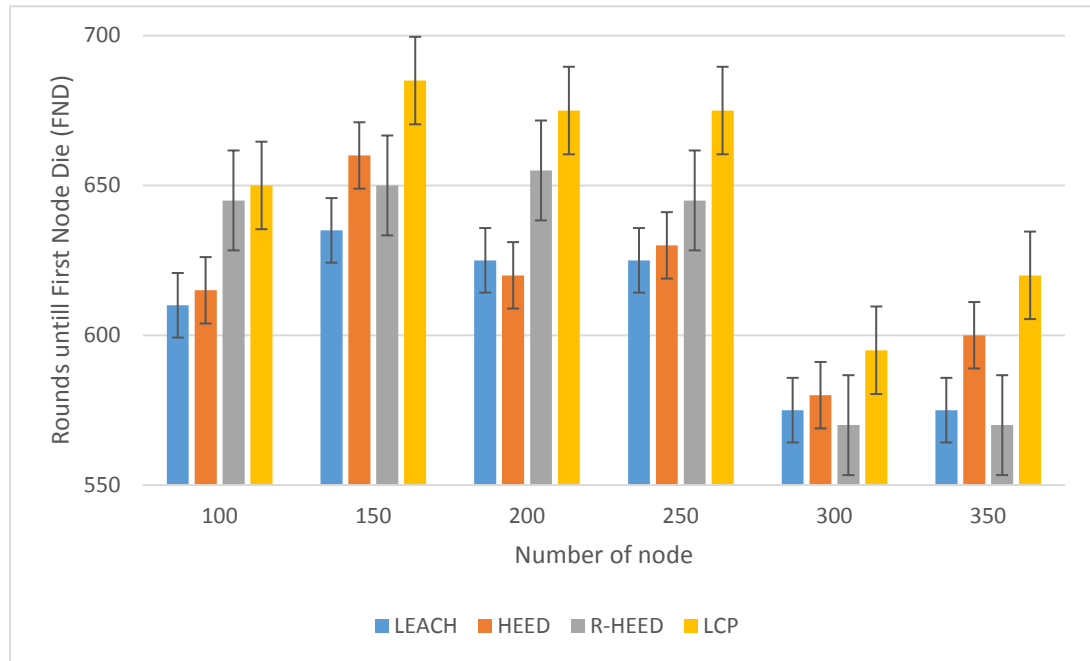
Figure 4.7. Network lifetime up to the FND in LEACH,
HEED, R-HEED, and LCP.

Figures 4.8 demonstrates rounds until the HND in the four protocols examined in the networks of diverse number of nodes. It is evident from the results that LCP performs better than the other protocols in HND in all groups of networks. LCP performs best and equally in the 100, 250 and 350 nodes compared to the other sets. In the networks of 150,200 and 300 nodes the LCP also performs equally but with a slight decrease.   In comparison with the other three protocols in their best performance in networks, LCP is more efficient by 4.41% than HEED in 150 and 200 nodes. LCP also perform better by 10.75% and 18.23% than R-HEED in 250 and LEACH in 200 respectively.
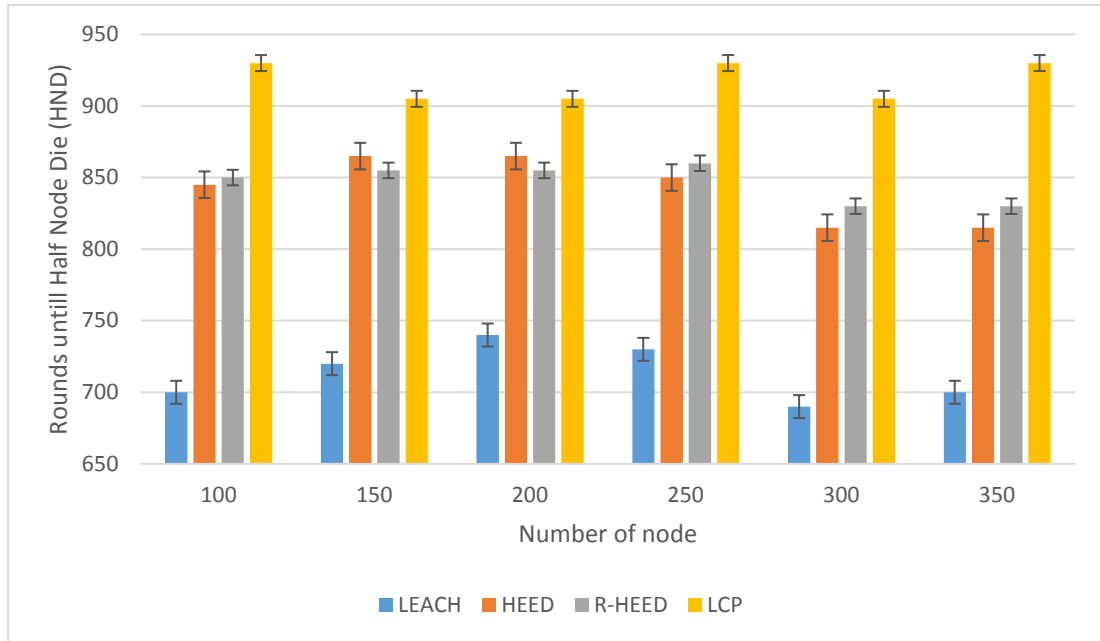
Figure 4.8. Network lifetime up to the HND in LEACH, HEED, R-HEED, and LCP.

Figures 4.9 shows rounds until the LND in the four protocols examined in the networks of diverse numbers of nodes. The results demonstrate that LCP lasts longer than the other protocols in LND in all groups of networks. LCP performs best in the
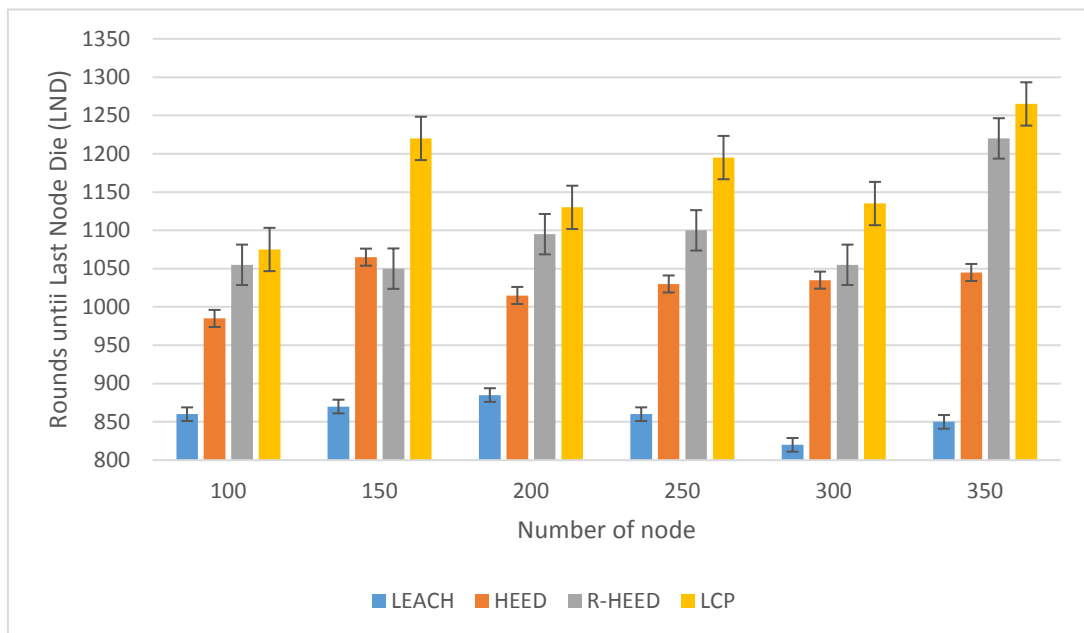
Figure 4.9. Network lifetime up to the LND in LEACH, HEED, R-HEED, and LCP.

350 nodes compared to the other sets. In the rest of the networks LCP performance falls gradually in 150, 250, 300, 200 and 100 networks. In comparison with the best of other three protocols, LCP is more efficient by 3.55% than R-HEED in 350 network size. In addition, LCP is more efficient by 12.70% and 21.68% than HEED in 150 nodes and LEACH in 200 nodes respectively.

Delivered data messages: Figure 4.10 shows quantity of the delivered data messages in single round. It is evident form the results that the amounts of data delivered are comparable across all protocols. The differences in the volume of the data delivered from the start of the experiment until the completion of the first round are minimal.
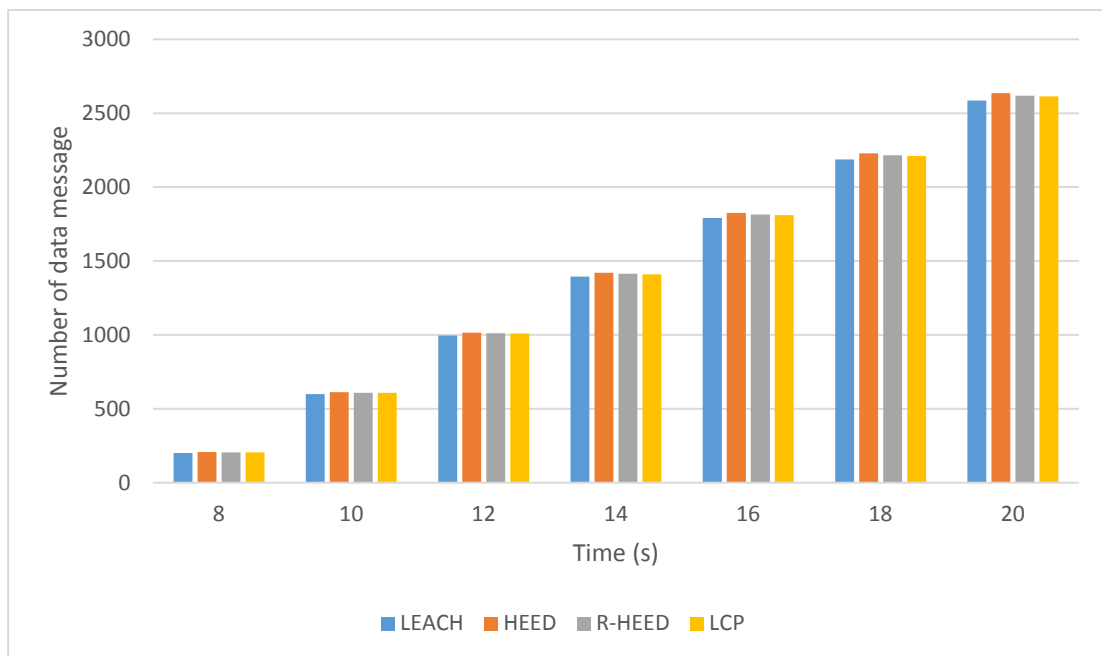
Figure 4.10. Number of the delivered data messages per round.

It can be easily observed from the simulation results that, when the number of the nodes increases, the percentage improvement also increases. Therefore, it can be reasoned that when the number of nodes is increased, the amount of energy consumed during the clustering phase decreases. However, such energy reduction does not affect the number of the data messages sent to the BS. Thus, the energy

saved due to this new clustering scheme will be maximised, which will improve the network lifetime.

4.7   Conclusion

Energy consumption is a significant concern in WSNs. Although cluster-based protocols belong to the most efficient energy solutions, they still suffer from the energy waste during the clustering process. To load balance CH election in cluster-based protocols, the network needs to go through a new election process every round. Significant energy and time are consumed during this interactive clustering process, especially at the setup phase of every round.

In this chapter, we proposed a new technique, LCP, which introduces a new inter-cluster method. To reduce the number of iterative clustering processes, LCP continuously rotates the CH election within the same CM. The node with the highest energy has the priority to become a CH in each round. This new technique aims to prolong the lifetime of the whole network and to extend the network lifetime without compromising the QoS. The performance evaluation in terms of network lifetime was conducted using the Castalia simulator. We compared the original LEACH, HEED, and R-HEED protocols with the new technique under the same simulation conditions and parameter values. Results demonstrate that the proposed protocol has improved the performance in terms of decreasing energy consumption and increasing the total network lifetime. This is witnessed while LCP maintains performance in regards to the quantity of the data transmitted to the BS.

Based on the simulation results, the LCP significantly outperforms its counterparts in terms of several performance metrics. The results show that LCP has reduced the rate of the setup phase messages by 6.4%, which has consequently reduced energy consumption by 26.79%. Therefore, the LCP improves the network lifetime by 4.5%, 8.33%, and 4.21% for FND, HND, and LND, respectively. Although the increase in lifetime is not very large, it is still important in many real-time applications.

In this chapter, LCP is tested and evaluated against other cluster-based routing algorithms using simulations. Although there has been improvements in energy

consumption and network lifetime, we believe that, by considering an unequal cluster by forming a smaller cluster size that is smaller and closer to the BS and a larger cluster that is further away, we achieve a further reduction in energy consumption. This concept will be discussed in the next chapter.

Chapter 5

Efficient Dynamic Load-balancing-aware

Protocol for Wireless Sensor Networks

5.1   Background and Motivation

Cluster-based routing protocols for WSNs quite often suffer from an inequitable distribution of CH nodes within the network, and this can cause increased energy waste [57]. Therefore, equitability in terms of load distribution is an essential condition, which needs to be considered when designing a cluster-based routing protocol. An instance of an inequitable state is that which pertains when clusters of different sizes are randomly formed; thus, some CH nodes may turn out to be a long way from the BS [70]. This can lead to an imbalance in energy consumption among the clusters and will consequently affect the total performance of the network.

The previous chapter discussed a new LCP protocol [133], which significantly decreases the consumption of the energy in the WSNs by reducing the frequency at which the setup phase must be undertaken. In this chapter, we propose a new energy-aware clustering protocol called the Dynamic Load-balancing-aware Protocol (DLCP) [114]. This addresses the load-balancing issue in cluster-based routing protocols. First, the DLCP protocol divides the node clusters into groups according to sizes. The clusters that are closer to the BS are of a smaller size than those that are further away. This unequal-size cluster topology can reduce the imbalance that will exist in relation to energy consumption. Second, DLCP pre-defines the interval timer depending on the remaining energy of the nodes at the beginning of each round. This action delays the frequency at which the re-clustering message will be triggered by the BS. The CHs continue to rotate the leadership among them, within the same CMs, by electing the node with the highest residual energy in each round. When the energy of one CH falls below a fixed threshold CH (T_{CH}), a new clustering process will be created. Figure 5.1 shows the arrangement of an unequal-size cluster topology.
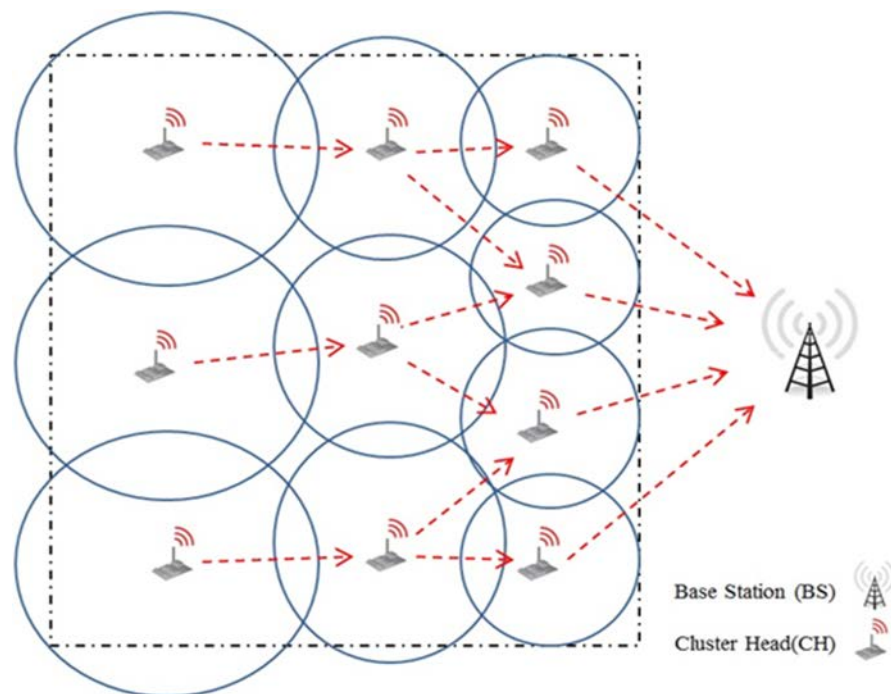
Figure 5.1 Unequal cluster topology.

5.2   Proposed Mechanism

The design of the proposed mechanism was based on the successes of HEED [111] and EEUC [123]. These two clustering protocols were modified to create a new energy-efficient clustering protocol. This modified protocol is called the DLCP. The round time of DLCP has two phases: the setup phase followed by the steady-state phase (as in HEED and EEUC). At the setup phase, initiated at the beginning of each round, all nodes compute their competition range (R_{comp}), according to Equation 5.1.

$$s_i . R_{comp} = \left(1 - c\frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}}\right) R_{comp}^0, \qquad 5.1$$

where d_{max} and d_{min} denote the maximum and minimum distances between the SNs and the base station, $d\ (s_i, BS)$ is the distance between s_i and BS, c is a constant coefficient (0-1), and $R^o{}_{comp}$ is the maximum value of the cluster radius.

This function identifies the distances to the BS and helps to form the clusters of different sizes. The smaller sized clusters are located closer to the BS, whereas the larger clusters are situated further away from the BS. All nodes 'agree' to start the time interval process to select several candidate CH (C_{CH}) nodes. The nodes with higher energies have higher priorities in terms of becoming C_{CH} nodes. After this
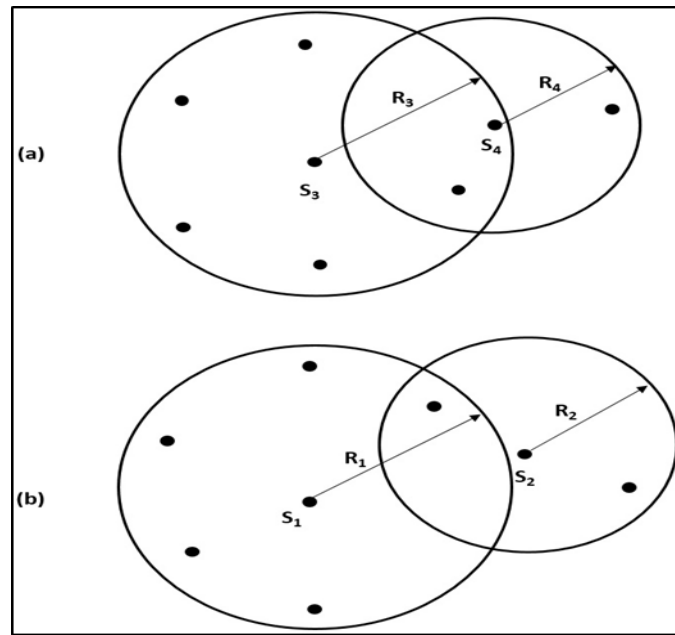
Figure 5.2. Different competition ranges of candidate
cluster heads.

stage, only the nodes that were selected as C_{CH} become active and compete to become F_{CH}. The remaining nodes, which were not selected as C_{CH} nodes, remain in sleep mode till the final CH (F_{CH}) is selected from the C_{CH} nodes. The nodes with the highest R_{comp} will win the competition to become a F_{CH}. Figure 5.2 shows the topology of a network in relation to C_{CH} nodes.

Here, the circles illustrate the different competition ranges of the C_{CH} nodes. In Figure 5.2(b), s_1 and s_2 can both be F_{CH}. However, in Figure 5.2(a), s_3 and s_4 cannot be F_{CH} because they are within the range of another cluster. Thus, the employment of CHs nodes can be observed across the network.

In the DLCP protocol, the setup phase and steady phase are only present in the first round. In the second round, the DLCP protocol will maintain the clusters as they are and choose the next available CM with the highest residual energy within the same cluster to become its new F_{CH}. This process reduces the number of setup phases that must be undertaken in each round; this is a similar process to that which the LCP protocol goes through. The leadership of the CHs will continue to rotate among the CHs within the same cluster via the selection in each round of the node with the highest energy. If one of the CHs reaches a particular threshold (T_{CH}), which is calculated according to Equation 5.2, a new clustering process will begin:

$$(T_{CH}) = \frac{\sum E_{Residual}}{N} - 1, \qquad 5.2$$

where n is the number of nodes in the cluster and $E_{Residual}$ is the sum of the residual energies in the cluster at the beginning of the last round in which re-clustering occurred.

The DLCP is similar to HEED in terms of the following features:

- The elected CHs send an advertisement message to nodes within the cluster.

- The network is homogeneous and all SNs have the same initial Energy capacity.
- The cluster formation 'setup phase' finishes in O (1) iterations.

- Each node can join one cluster only and communicates directly with its CH.
- During the cluster formation process, a node can become either a C_{CH} or a F_{CH}, or it can be 'covered'.
- At the end of the clustering procedure, the F_{CHs} form a network backbone. Thus, the data are forwarded in a hop-by-hop manner between F_{CHs} until it reaches the BS.

5.3   Implementation

In DLCP, the clustering operation is divided into several rounds. Each round has two phases: the setup phase and the steady-state phase. The setup phase is divided into four stages: 1) initialisation stage, 2) repeat stage, 3) finalisation stage and, 4) rotation stage. The following subsections describe these proposed phases in more detail. Table 5.1 shows the control packets used in DLCP.

Table 5.1. DLCP control packet parameters.

Message	Description
Hell_msg	(NodeID, ResidualEnergy)
Candidate_msg	(NodeID, CCH, cost)
Final_msg	(NodeID, FCH, cost)
Compete_msg	(NodeID, RComp, ResidualEnergy)
Join_CH_msg	(NodeID, ResidualEnergy)
Schedule_msg	(Schedule order, Threshold)
Rclust_msg	(NodeID, FCH)

5.3.1   Initialisation Stage

Similar to that which happens with HEED, at the beginning of this stage, each SN is allocated an initial percentage, CH_{prob}, based on its remaining energy. Then, nodes set their competitive radius R_{comp}, as defined in EEUC, to organise an unequal-cluster network. All nodes generate a random value (RnN) in the range (1, 0) and set their C_{CH} to false as a default values at this phase. The pseudocode of the initialisation stage is given in Algorithm 5.1.

Algorithm 5.1 Initialisation stage

1: **procedure** SET AN INITIAL PERCENTAGE OF CHS
2:     **for** each node **do**
3:         set with CH probability ← CH_{prob}
4:         set with competition range ← R_{comp}
5:         set with CH previous ← $CH_{previous}$
6:         set with Random $(0,1)$ ← RnN
7:         set with Not CH status C_{CH} ← $false$
8:     **end for**
9: **end procedure**

5.3.2 Repeat Stage

In this stage, several nodes are elected as C_{CHs} via the broadcasting of several Candidate_msg. Only nodes that have the highest energy value encountered at this phase can become F_{CHs}. They will then broadcast the Compete_msg (NodeID, RComp, and ResidualEnergy) to all nodes within their radio range. If a node is determined to be not a candidate_CH during this phase, then it declares itself a non_CH by sending a Join_CH_msg (NodeID, ResidualEnergy) to its closest F_{CH}. The pseudocode of the repeat stage is given in Algorithm 5.2.

Algorithm 5.2 Repeat stage

1: **procedure** SELECT CANDIDATE CH
2:     **while** $(CH_{previous} < 1)$ **do**
3:         **if** (SET C_{CH} isNotEmpty()) **then**
4:             **if** $(MyNode = highest \quad En \quad (C_{CH}))$ **then**
5:                 Broadcast Compete message
6:                 EXIT
7:             **else**
8:                 Broadcast Candidate message
9:             **end if**
10:         **else**
11:             **if** $(RnN < CH_{prob})$ **then**
12:                 Broadcast Candidate message
13:             **end if**
14:         **end if**
15:         $CH_{previous}$ ← CH_{prob}
16:         CH_{prob} ← $min(CH_{prob} * 2, 1)$
17:     **end while**
18:     **if** $(SET\_C_{CH}$ isEmpty()) **then**
19:         Broadcast Compete message
20:     **end if**
21: **end procedure**

5.3.3   Finalisation Stage

In this stage, each C_{CH} node makes the final decision when it becomes an F_{CH} by checking whether there is a C_{CH} node with more residual energy than itself within the radius R_{Comp}. If a C_{CH} node discovers C_{CH} node with more energy within the cluster, it will give up the competition and will become a non-CH. In the case that there is no other C_{CH} with a higher residual energy, a particular C_{CH} will elect itself as the F_{CH} and will broadcast this detail to all the nodes in its cluster range. The pseudocode of the finalisation stage is given in Algorithm 5.3.

Algorithm 5.3 Finalisation stage

```
1: procedure SELECT FINAL CH
2:      On receiving a COMPETE message form node n_j
3:      if (d(n_i, n_j) < n_j.R_comp OR d(n_i, n_j) < n_i.R_comp) then
4:          F_CH ← true
5:          Broadcast Final CH message
6:      end if
7: end procedure
```

5.3.4   Rotation Stage

After each F_{CH} node has formed its cluster in the first round, each CM node reports its residual energy to its relevant F_{CH} before the network enters the steady-state phase. The F_{CH} can compute the threshold (T_{CH}) of its cluster using Equation (5.2). Then, each F_{CH} constructs a turning schedule to inform every CM when they can expect to become a CH. The turns are sorted out based on the residual energies in each SN. Thus, the node with the highest residual energy will be the first candidate to become the F_{CH} in the next round.

Consequently, at the beginning of the next round, it is not necessary to re-cluster the entire network as in HEED and EEUC. The nodes within the same cluster in subsequent rounds continue rotating the F_{CH} role between them by selecting the node with the highest residual energy in each round. If the residual energy of (at least) one F_{CH} falls below a threshold (T_{CH}), it informs the BS of this by sending a re-cluster message via a multi-hop route. The BS will then re-broadcast the message across all the nodes to notify them that a new clustering process must be started. When all

nodes have received the re-clustering message, they will then proceed to the initialise stage. The pseudocode of the rotation stage is given in Algorithm 5.4.

Algorithm 5.4 Rotate stage

1: **procedure** SELECT CH NEXT ROUND
2:     Nodes Wait for interval of time
3:     **if** $(Node_{En} < T_{CH})$ **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   Simulation Scenarios and Results

In the simulation experiment, we evaluated the performance of the DLCP protocol using the commonly used, open-source Castalia simulator [141], as stated in the previous chapter. We considered a sensor network composed of (100–350) SNs randomly deployed in a $250\,\text{m} \times 250\,\text{m}$ square region. All the SNs were fixed, homogeneous and started with the same level of energy. The BS is situated outside the sensor field. The primary energy of each node is 25 J and the energy consumption is calculated via the data transmission and aggregation carried out in each round. In all the simulation scenarios, the (CC2420) radio type was used. Table 5.1 gives an overall summary of the simulation parameters.

As previously mentioned in Section 4.5, the most important metrics for measuring energy consumption are the setup messages overhead, total energy consumption, and network lifetime. The same scenarios are applied to the new, proposed, routing module, along with the above-mentioned parameters to evaluate the energy performance of the network under this scheme. Thus, we compared the performance indices of DLCP against EEUC and HEED. First, we tested the proposed protocol by calculating the setup message overhead incurred by various numbers of nodes. Second, we calculated the total energy consumption. Third, we measured the network lifetime via three different metrics: FND, HND, and LND. Lastly, we observed the outcome of the delivered data messages to the BS.

Table 5.2. DLCP protocol simulation parameters.

Parameter	Value
Sensor field	250 m x 250 m
Deployment method	Uniform, Random
Simulation time limit	500–1100 seconds
Sensor network number of nodes	100, 150, 200, 250, 300, 350
Initial energy	25 Joules
Wireless channel-only static nodes	True
Application ID	Throughput test
Sensor Node 0 is sink	True
Sink node location	(300, 125)
Report destination is sink	True
Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	LPC, EEUC, HEED

5.4.1   Setup Messages Overhead

Figure 5.3 compares the number of messages involved in the setup phases of EEUC, HEED, and DLCP, respectively, in relation to a 100 second simulation time and with various numbers of nodes.
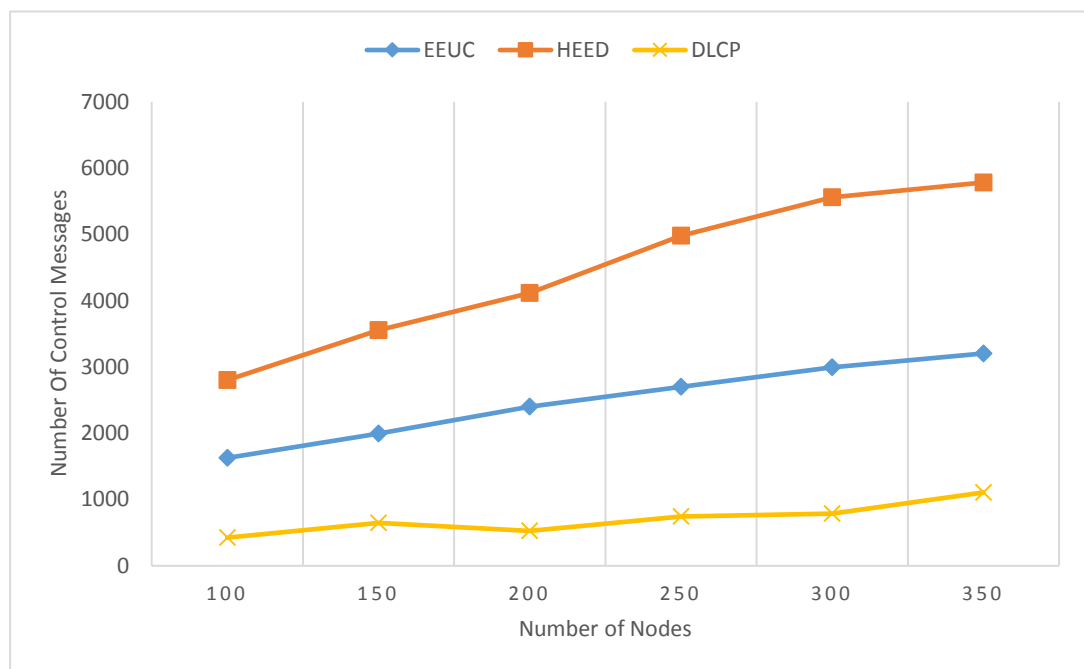
Figure 5.3. Average number of setup messages in EEUC, HEED, and DLCP.

The DLCP generates between 425 and 1107 messages, while EEUC generates between 1628 and 3204 messages, and HEED generates between 2802 and 5784 messages. It can be concluded that DLCP has the lowest rate in terms of setup messages by approximately 28.17% compared to its peers. Thus, this indicates that DLCP provides the greatest reduction in terms of energy consumption.

5.4.2   Energy Consumption

Figure 5.4 demonstrates the relationship between the consumption of energy and the simulation time for a network of 100 nodes. It is evident that DLCP consumes the least amount of energy when compare to EEUC and HEED. The average reduction is 1.97 J (7.88%) when compared to HEED and 7.031 J (28.124%) when compared to EEUC.
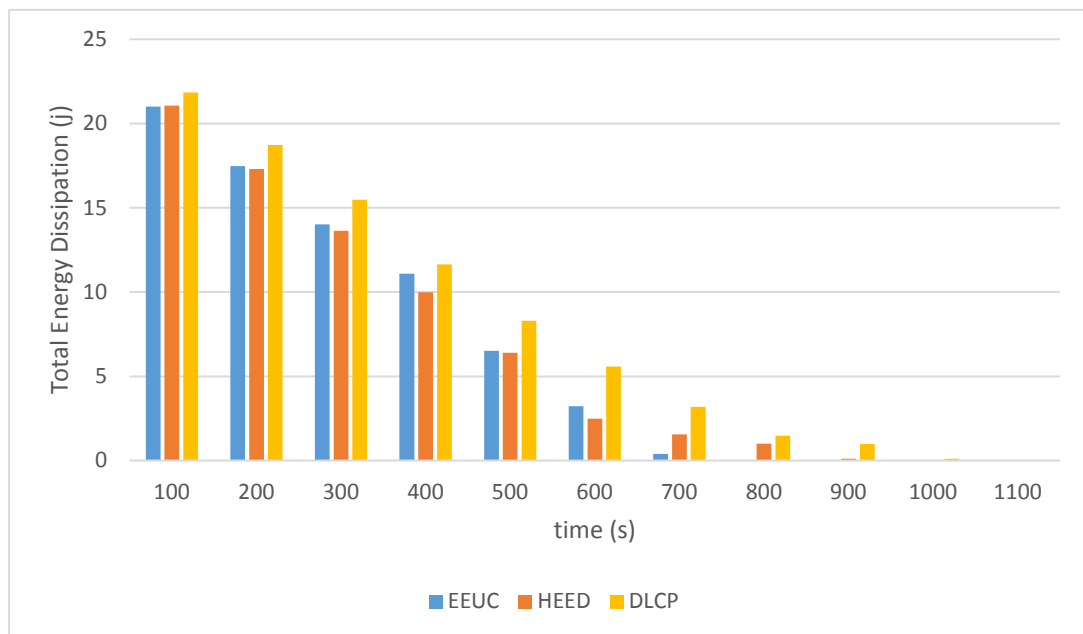
Figure 5.4. Remaining energy in EEUC, HEED, and DLCP.

The reduction in setup message overheads and energy consumption consequently prolongs lifetime of the network. Figure 5.5 demonstrates the total number of nodes remaining live after the prescribed simulation period, measured in the network of 100 nodes. It can be seen that DLCP considerably increases network lifetime compared to its peers. The average network lifetime of EEUC protocol is 800 seconds, and 950 seconds in HEED protocol. Therefore, the new approach of using
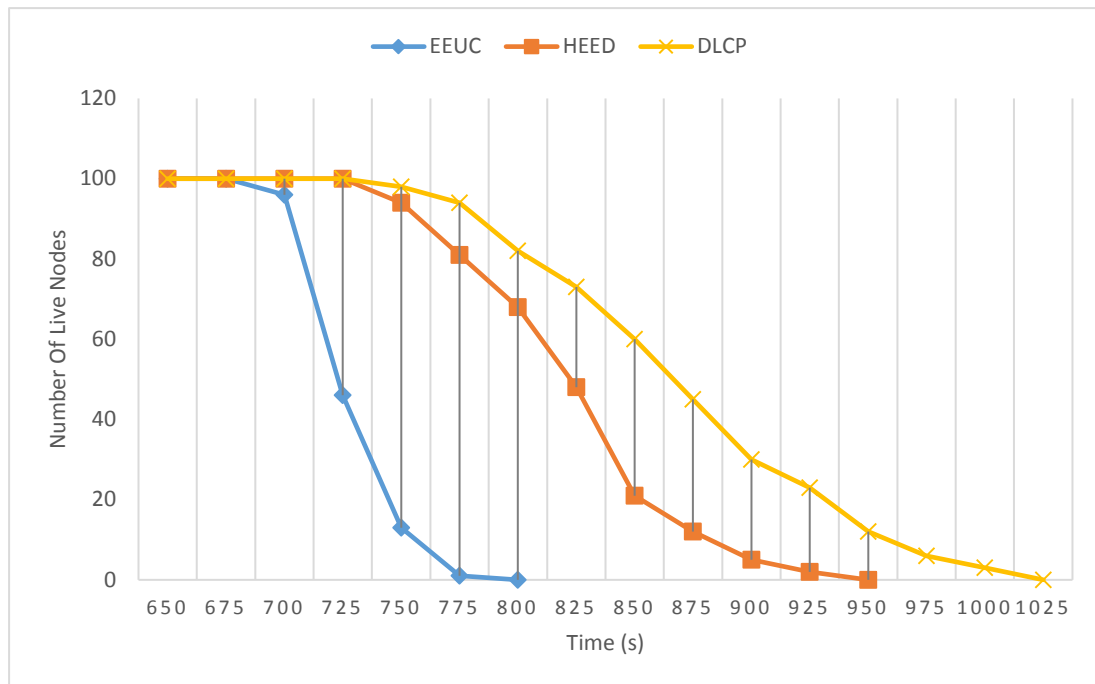
Figure 5.5.Number of live sensors vs numbers of.

the unequal-cluster algorithm and a threshold for starting a new round increases network lifetime by at least 10%. When comparing the network lifetime metric of LCP with DLCP, the results differ slightly. This can be due to the parameters changes, such as the size of the network field.

5.4.3   Network Lifetime

As mentioned in the previous section, DLCP prolongs network lifetime by at least 10%, when considering networks of 100 nodes. To further validate the proposed protocol, additional evaluations were conducted using different lifetime metrics FND, HND, and LND in relation to networks ranging from 100 to 350 nodes in size. The performance of DLCP is compared to EEUC and HEED protocols in all sets of network.

Figure 5.6 shows the network lifetimes, that is, in this case, the times until the FND, as the number of nodes varies between 100 and 350. The DLCP significantly outperforms its counterparts in all sizes of network, and the highest performance is achieved in the network of 200 nodes, then decreases gradually in 150, 100. In the network of 300 and 350 nodes DLCP performs equally but decreases further in 250

nodes. In comparison with the other two protocols in their best performance in networks, DLCP is more efficient by 2% than HEED in 100 nodes and 5.80% then EEUC in 200 and by 1.34% in 350 nodes.
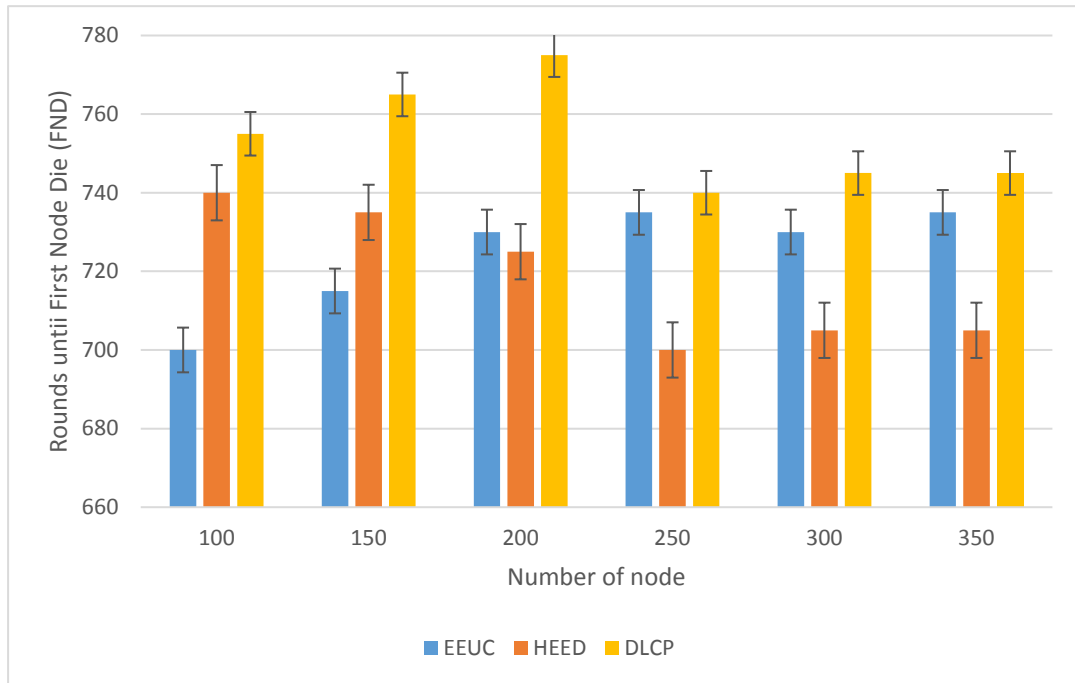
Figure 5.6.Network lifetimes up to the FND in EEUC, HEED, and DLCP.

Figure 5.7 shows the lifetime of the network as measured by the period until HND. Again, DLCP outperforms the EEUC and HEED protocols in all sets of networks. The DLCP performs best at 350 nodes, however its performance decreases only marginally in the other sets of networks. In comparison with the other two protocols best performance, DLCP is more efficient by 4% and 14% than HEED in 150 nodes and EEUC in 350 nodes respectively.

Figure 5.8 demonstrates the lifetime of the network as measured by the period until LND. Comparable with the previous results DLCP outperforms the EEUC and HEED protocols in all sets of networks. DLCP performs best in 250 nodes, then its performance decreases slightly in other sets of network, having the lowest performance in the network of 150 nodes. In comparison with the other two protocols in their best performance in networks, DLCP is more efficient by 1.85% and 21% than HEED in 200 nodes and EEUC in 350 nodes respectively.
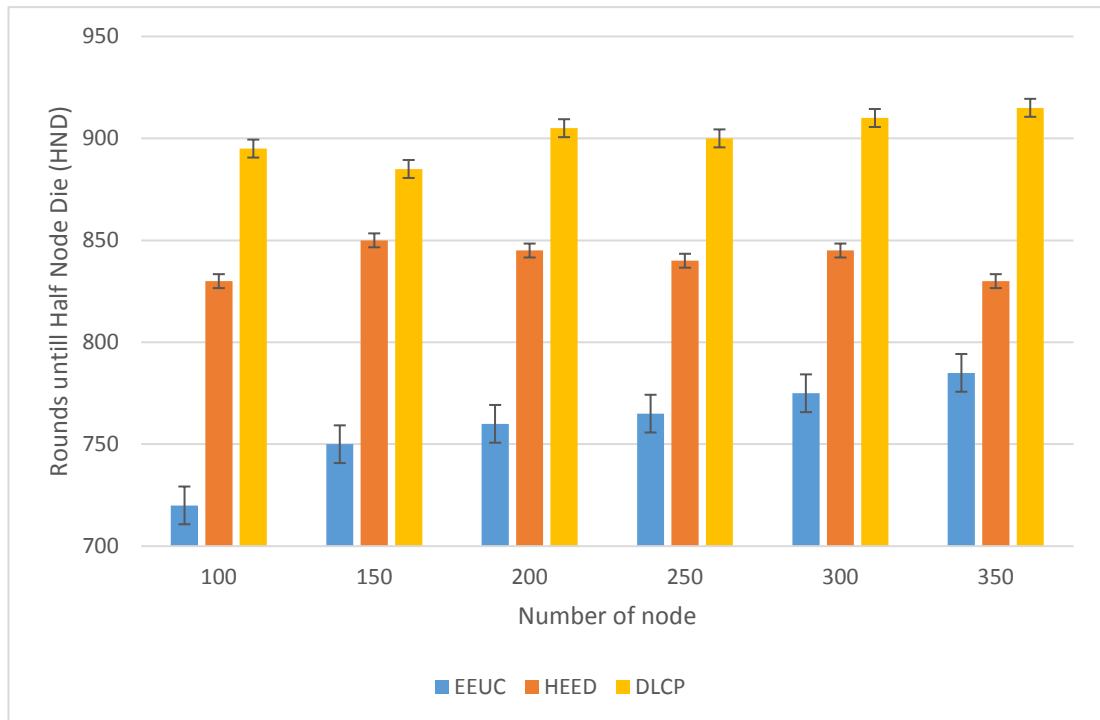
Figure 5.7. Network lifetimes up to the HND in EEUC, HEED, and DLCP.
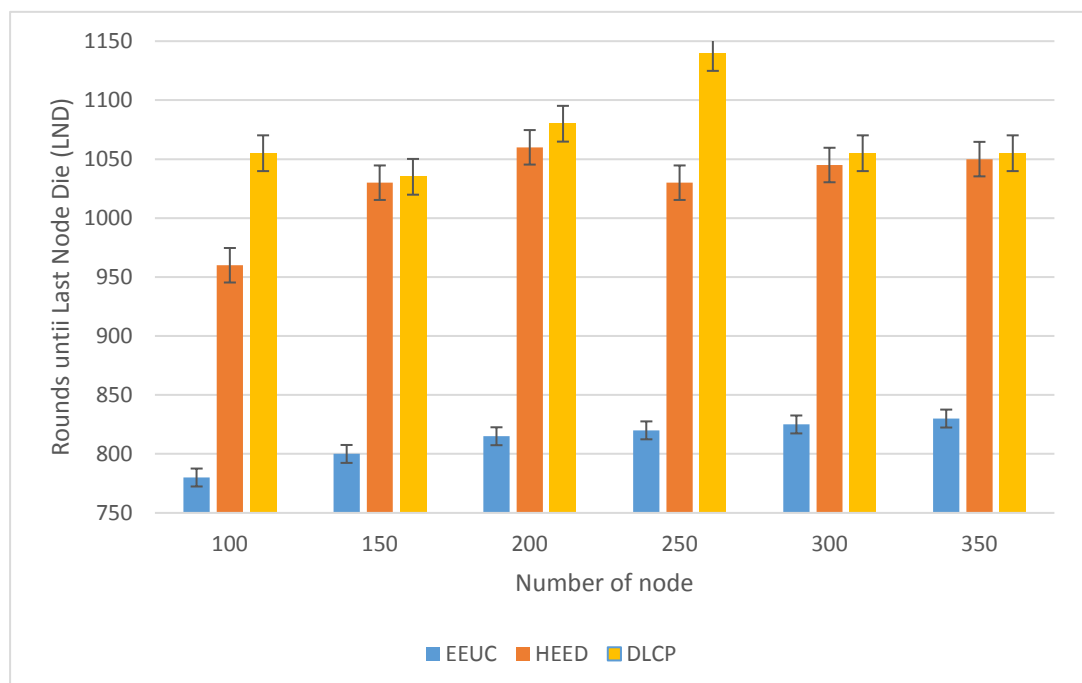
Figure 5.8. Network lifetimes up to the LND in
EEUC, HEED, and DLCP.

The last three experiments, involving networks of 100 to 350 nodes, confirm the previous research regarding network lifetimes. The rotating process reduces the energy consumption among the nodes and significantly increases network lifetime. It may be easily observed from the simulation results that, when we increase the number of nodes, the percentage improvement resulting from the use of DLCP compared to that of EEUC or HEED increases.

5.4.4 Delivered Data Messages

Although the QoS was not directly measured by the experiments, it is clearly important to consider this metric. The data messages sent by nodes towards the BS over time a gradual increase, almost the same amount of data is delivered when using all three protocols: EEUC, HEED, and DLCP. Thus, this indicates that DLCP increases network lifetime without affecting the amount of delivered data to the BS.

5.6 Conclusion

In the previous chapter, we proposed a LCP. The LCP significantly improved network lifetime by utilising an inter-cluster technique to reduce the number of interactive clustering processes. However, the inequity of CH node distributions within the network can cause the early death of nodes. In this chapter, an advanced version of LCP has been proposed to address this problem.

The main contributions of this advanced version, called the DLCP, are as follows. First, the DLCP forms unequal-size clusters to achieve load balancing of energy among clusters. Second, it utilises a dynamic rotation technique to achieve load balancing of energy within clusters. A performance evaluation, in terms of network lifetime, was conducted using the Castalia simulator. We compared the original EEUC and HEED protocols with DLCP, the advanced version of LCP, under the same simulation conditions and parameter values as applied to LCP. The results show that the proposed technique improved the performance of networks in respects to decreasing the use of the energy and increasing the lifetime of the network.

Based on the results of simulations carried out on a network of 100 nodes, DLCP significantly outperforms its counterparts in terms of several performance metrics.

The results show that the use of DLCP reduces the number of setup phase messages by approximately 28.17%, which consequently improves energy consumption by 7.88% when compared to HEED and by 28.124% when compared to EEUC. Additionally, further evaluation, based on the FND, HND, and LND metrics in relation to networks ranging from 100 to 350 nodes, confirms the network lifetime improvements, which can be achieved by DLCP. The improvements achieved using DLCP in relation to these metrics are significant when compared to EEUC and HEED, which are by 5.006%, 7.352%, and 4.060% for FND, HND, and LND, respectively. Thus, the proposed technique decreases energy consumption and increases total network lifetime without compromising QoS.

At this point, two energy-efficient protocols (LCP and DLCP) have been proposed that significantly decrease consumption of the energy. The election of the CH in both protocols is based on a single metric (remaining energy). It can be argued that considering additional metrics when selecting CHs could further improve the performance of these protocols and consequently improve the network lifetime. In the following chapter, we propose a new protocol that does consider additional metrics when selecting CHs.

Chapter 6

Weight-Driven Cluster Head Rotation for Wireless Sensor Networks

6.1 Background and Motivation

In cluster-based protocols, the CH node carries out additional transition tasks compared to the CM [150]. Thus, CHs consume extra energy during the network processes, which can lead to the early death of the nodes and cause network failure. Selection of an optimal CH can greatly affect the energy efficiency of the network. Nevertheless, the question of how to select the optimal CH remains a frequently encountered challenge in cluster-based protocols [104]. Indeed, a CH can be elected based on node quality, which may be based on different metrics, such as residual energy, node degree, connectivity, and node distance from its neighbours. Significant improvement in performance and quality can be achieved by combining these metrics [151].

In Chapters 4 and 5, two efficient energy-aware cluster protocols for WSNs LCP [11] and DLCP [114] have been proposed to reduce energy consumption and increase network lifetime. In LCP, a new inter-cluster technique was designed to reduce the amount of energy waste in the setup phase of each round. In DLCP, the network is divided into unequal-size clusters and a dynamic inter-cluster technique based on threshold (T_{CH}) values is utilised to start a new cluster process. In this chapter, we present an energy-aware clustering protocol, called a Weight-Driven Cluster Head Rotation (WDCR) [152], to achieve a better energy balance among CHs and higher energy efficiency in WSNs. In WDCR, the selection of the CHs is based on a combined weight metric that considers the following system parameters: remaining energy, CH frequency, and node distance to the BS. The sensor network field is divided into unequal-cluster sizes, similar to DLCP. The CH continues to rotate the leadership within the same CMs by selecting the node with the greatest weight in each round.

6.2   Proposed Mechanism

6.2.1   Weight Metrics

The WDCR protocol combines a weighted technique and a cluster-based routing protocol. The selection of the optimal CH within the cluster is based on residual energy of the node, CH frequency, and node distance to the BS. The advantage of using these metrics is to select the optimal CHs that require less energy for transmitting the data.

Remaining energy (ENR): Since the SNs are battery-powered devices that consume considerable energy during the network process, the residual energy might be employed as a metric for selecting the CHs. This is expressed in Equation 6.1 where E_j is the remaining energy of node j and E_{max} is the maximum remaining energy among the neighbour's nodes:

$$ENR_j = \frac{E_j}{E_{max}}.\qquad\qquad 6.1$$

Cluster head frequency (CHF): A CH that has been previously selected more than once, has consumed more energy and has less chance of being selected again in

order to balance the CH task load among the SNs. Therefore, CH frequency is considered a weight metric. It is expressed by Equation 6.2, where CHF is the number of times node s_j becomes a CH:

$$CHR_j = \frac{1}{CHF_j}. \qquad 6.2$$

Node distance to the BS (DBR): In one-hop communication, the nodes located far away from the BS utilise more energy, as they must transmit the data over a long distance. However, in multi-hop communication, the nodes located close to the BS consume more energy and die first because of a heavy relay traffic load. Therefore, the distance of the node to the BS is considered a weight metric. Equation 6.3 exhibits the distance between node s_j and the BS:

$$D_j = \sqrt{(x_j - x_{BS})^2 + (y_j - y_{BS})^2}. \qquad 6.3$$

The optimal neighbour s_j distance is determined by Equation 6.4, where D_{min} is the neighbour's node with shortest distance to the BS, and D_j is the s_j distance to the BS:

$$DBR_j = \frac{D_{min}}{D_j}. \qquad 6.4$$

In order to select the optimal CH we consider the same weight constant for all three metrics. Each SN calculates the final weight using Equation 6.5, where $w_1 = w_2 = w_3 = 0.33$ as weight constants:

$$WR = w_1 \times ENR_j + w_2 \times DBR_j + w_3 \times CHR_j. \qquad 6.5$$

6.2.2   Unequal Cluster

Different cluster sizes can also affect energy consumption among CHs. Thus, we use an unequal-cluster algorithm based on an EEUC protocol [123] in which we form small clusters close to the BS and larger clusters farther away. The distribution is constructed by the competition radius, calculated in Equation 6.6 which is same as Equation 5.1.

$$s_i.R_{comp} = \left(1 - c\frac{d_{max} - d(s_i, BS)}{d_{max} - d_{min}}\right) R_{comp}^0. \qquad 6.6$$

where d_{max}, d_{min} represent the maximum and minimum distances to the BS, respectively, and $d\,(s_i, BS)$ denotes the distance between s_i and the BS. Moreover, R^0_{comp} is the maximum value of the cluster radius, and c is a constant coefficient between 0 and 1:

6.2.3   Threshold

To reduce the message exchange overhead during the setup phase for each round, we propose a weight-driven CH rotation approach. The WDCR continuously rotates the CH selection among the same CMs. The node with the greatest weight has priority in becoming the CH in each round. This is expressed by Equation 6.7.

$$T_{CH} = 1 - \frac{\sum w}{N}\,.$$

6.7

where N is the total number of nodes in the cluster and w is the total weight of the node in the cluster.

6.3   Implementation

The proposed protocol is designed to address the challenge of selecting the optimal CH. The operating time in the WDCR protocol is divided into rounds. Each round contains three phases: a setup phase, a steady-state phase, and a rotation phase. A number of control packets are needed to complete these phases. Table 6.1 shows the control packets used in WDCR.

To simplify our network design, we adopt a few rational assumptions as follows:

- There are *N* SNs that are distributed in an M X M square field.

- Each node has an identity (ID).

- All the nodes and the BS are stationary after deployment.

- All SNs can be heterogonous, but their energy cannot be recharged.

- All SNs are location aware.

- All nodes can use power control to vary the amount of transmit power.

- The BS is out of the sensor field and it has a sufficient energy resource. Each node knows the location of the BS.

Table 6.1. WDCR control packet parameters.

Message	Description
Hell_Pkt	(selfID, selfEnergy, CHFj, selfDistant)
Head_Pkt	(selfID, selfWeight, selfRcomp)
Join_Pkt	(selfID, selfWeight)
Schedule_Pkt	(Schedule order, Threshold)
Route_Pkt	(selfID, selfWeight, selfDistant)
Rclust_Pkt	(selfID, selfFn)

6.3.1   Setup Phase

The primary purpose of the phase is to select the optimal CHs and to group the member nodes into the cluster. The setup phase is composed of the following stages.

Initialisation stage: At the beginning of this stage, each node computes its estimated distance to the BS as determined by Equation 6.3. To construct the network in an unequal-size cluster, all nodes calculate the competitive radius (R_{comp}) as defined in Equation 6.6. Subsequently, each node broadcasts a hello packet (Hell_Pkt) to all neighbour nodes. The Hell_Pkt includes the node unique identifier (IDj), remaining energy (Ej), the number of times the node has been selected as a CH (CHFj), and the node distance to the BS (Dj). Once the Hell_Pkt has been received, each node initialises its own parameters, remaining energy (ENRj) determined by Equation 6.1, CH frequency (CHRj) determined by Equation 6.2, and average distance to the BS (DBRj) determined by Equation 6.4. In addition, all nodes compute their own weight

```
Algorithm   6.1 Initialise Stage
 1: procedure SET AN INITIAL PARAMETERS
 2:      for each node do
 3:          set with competition range ← R_comp
 4:          set with remaining energy ← E_j
 5:          set with CH frequency ← CHF_j
 6:          set with node distance to BS ← D_j
 7:          set with Not CH status CH ← false
 8:          Broadcast Hello Packet
 9:      end for
10: end procedure
```

using Equation 6.5 and initialise the CH variable to false as the default value. The pseudocode of the initialisation stage is given in Algorithm 6.1.

Competition stage: In this stage, each node calculates its waiting time (T_w) based on its weight as defined in Equation 6.8. If node j does not receive a CH packet (Head_Pkt) when (T_w) expires, it sets the CH values to true and broadcasts Head_Pkt within the radio range. The Head_Pkt includes the node unique identifier (ID_j), the node weight (W_j) and the competitive radius (R_{comp}). Furthermore, to become the final CH (F_{CH}), each selected CH must make a final decision based on its weight. If the CH node has the greatest weight within the radius $R_{Comp,}$ it will declare itself a F_{CH}. In cases where there is another CH node within radio range with more weight, the CH node will give up the competition by declaring itself a non-CH. The non-CH nodes join the nearest F_{CH} by broadcasting join_Pkt. The pseudocode of the competition stage is given in Algorithm 6.2. Equation 6.8 is as follows:

$$T_W = \left(1 - \frac{W_j}{W_{max}}\right) V_r. \qquad 6.8$$

where W_j is the weight of node j, W_{max} is the maximum weight in the neighbour node, and V_r is a random value in [0.9, 1].

Algorithm 6.2 Competition stage
```
1: procedure SELECT CH
2:      On receiving a Head Packet n_j
3:      if (d(n_i, n_j) < n_j.R_comp OR d(n_i, n_j) < n_i.R_comp) then
4:          CH ← true
5:      else
6:          CH ← false
7:          Broadcast Join Packet
8:      end if
9: end procedure
```

Formation stage: The non-CH nodes join their nearest F_{CH} node with the highest received signal strength (RSSI) by sending Join_Pkt. The Join_Pkt includes the node unique identifier (ID_j) and the node weight (W_j). The F_{CH} node that receives the Join_Pkt adds the node unique identifier (ID_j) into its CM list. Once all the Join_Pkt have been received, the F_{CH} nodes compute the threshold (T_{CH}) within their clusters

using Equation 6.7 to generate a TDMA schedule and broadcast the schedule_Pkt to their CMs.

Routing path phase: At the end of the cluster formation stage, we set the interval time to construct a routing path on the selected F_{CH}. Each F_{CH} broadcasts a Route_Pkt within the radio range. The Route_Pkt includes the node unique identifier (ID_j), the node weight (W_j) and distance to the BS (D_j). After a F_{CH} node receives all Route_Pkt, it creates a routing table with all neighbour F_{CH}. If the distance from the F_{CH} to the BS is one hop, the F_{CH} sends the data to the BS as the next hop. Otherwise, the F_{CH} selects the F_{CH} with greatest weight and least distance to the BS as next hop, according to the routing table.

6.3.2   Steady-state Phase

The main goal of this phase is to exchange data among the SNs. As mentioned previously, there are two types of communication in the cluster-based scheme, namely intra-cluster and inter-cluster communication. Intra-cluster communication defines the communication within the cluster according to the time slot in the TDMA scheduling, where each CM transmits its data to its CH. The CH node aggregates the collected data from CM nodes to prevent duplicated transmission of similar events and transmits to the BS. Inter-cluster communication refers to the transition of data between the CHs and the BS. If the CH does not have long-haul communication competences, clustering algorithms have to determine the path between each of the CHs and the BS. The CH node selects the CH neighbour with the greatest weight and the shortest distance to the BS as a next hop.

6.3.3   Rotation Phase

The primary purpose of this phase is to reduce the rotation process (setup phase) of every round before the new cluster process occurs. Every fixed time, the F_{CH} task is rotated among the CMs within each cluster. The node with the highest weight in each cluster is selected as a new F_{CH} in the next round. The pseudocode of the competition stage is given in Algorithm 6.3. However, if the weight of the node falls below T_{CH}, the node broadcasts the Rclust_Pkt among the other nodes in order to start a new cluster process. The Rclust_Pkt includes the node unique identifier (ID_j)

and flags it, indicating a new clustering process (F_n). Therefore, at the start of the next round, a new re-clustering process for the entire network starts.

Algorithm 6.3 Rotation phase

1: **procedure** SELECT CH NEXT ROUND
2:     Nodes Wait for interval of time
3:         **if** ($W_j < T_W$) **then**
4:             Broadcast Re-cluster Packet
5:         **else**
6:             Select Next node as CH
7:             Broadcast Head Packet
8:         **end if**
9: **end procedure**

6.4   Simulation Scenarios and Results

This section describes the simulation environment that has been used to assess the performance of the WDCR. We evaluate the performance of the presented WDCR protocol using a Castalia simulator [141] that is built on the OMNeT++ platform and has been previously described in Section 4.4. The network performance index of WDCR is compared to the network performance index of LCP and DLCP. In the simulation models, we consider a network of 100–350 SNs, randomly deployed in a 250 m $\times$ 250 m square region. All the nodes are fixed after deployment and have limited stored energy. The BS is located outside the network field. The energy consumption for each SN is calculated by data transmission and aggregation per round. The simulation parameters are presented in Table 6.2.

Table 6.2. WDCR simulation parameters

Parameter	Value
Sensor field	250 m x 250 m
Deployment method	Uniform, random
Simulation time limit	500–1100 seconds
Sensor network number of nodes	100, 150, 200, 250, 300, 350
Initial energy	25 J
Wireless channel-only static nodes	True
Application ID	Throughput test
Sensor node 0 is sink	True
Sink node location	(125, 300)
Report destination is sink	True

Communication radio type	CC2420
Radio carrier frequency	2.4 GHz
MAC protocols	T-MAC
Routing protocols	WDCR, DLCP, LCP

6.4.1 Setup Messages Overhead

Figure 6.1. Shows a global comparison between WDCR, DLCP, LCP in regards to the number of messages operated at the setup phase for 100 seconds. High frequency of setup messages causes more energy waste and negatively affects the network performance. WDCR performs significantly better compared to LCP and marginally better than DLCP. Although DLCP performs slightly better in a network of less than 200 nodes, when the number of nodes increases, WDCR has the lowest rate of setup messages. The average improvement is 8%.
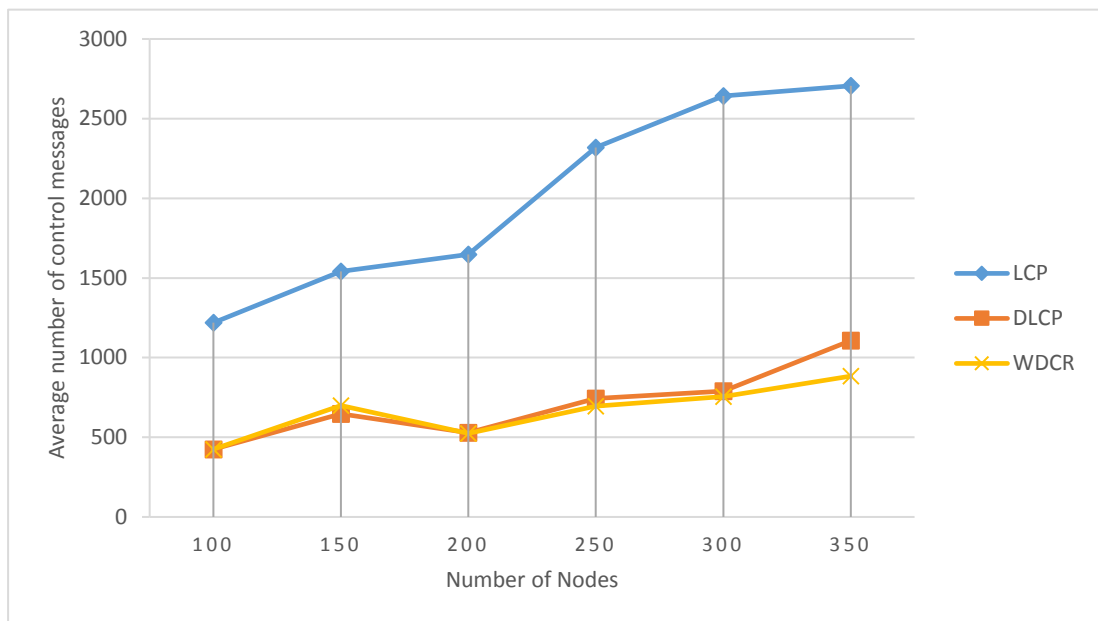
Figure 6.1. Average number of setup messages in LCP, DLCP, and WDCR.

6.4.2 Energy Consumption

Figure 6.2 demonstrates the relationship between energy consumption and simulation time for 100 nodes. The result shows that WDCR consumes the least amount of energy. The average energy consumption is reduced by 1.086 J (8.415%) when compared to LCP and by 0.57 J (4.542%) when compared to DLCP.
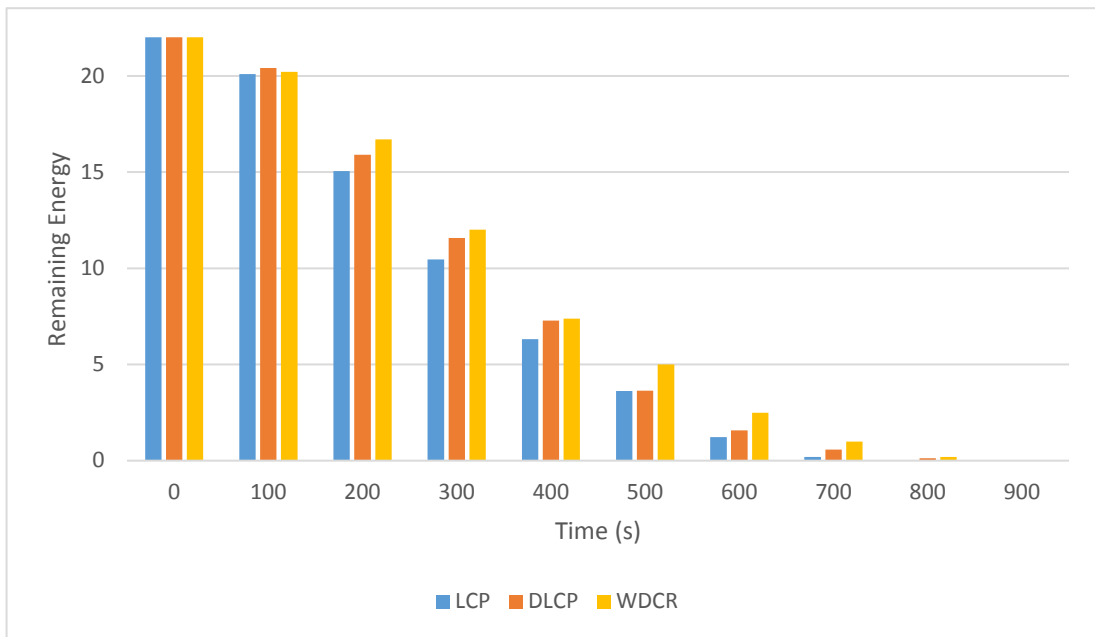
Figure 6.2. Remaining energy in LCP, DLCP,
and WDCR.

Figure 6.3 demonstrates the total number of nodes remaining live following the simulation time. WDCR increases the network lifetime compared to its peers. It is evident that WDCR consumes the least amount of energy. The average lifetime in
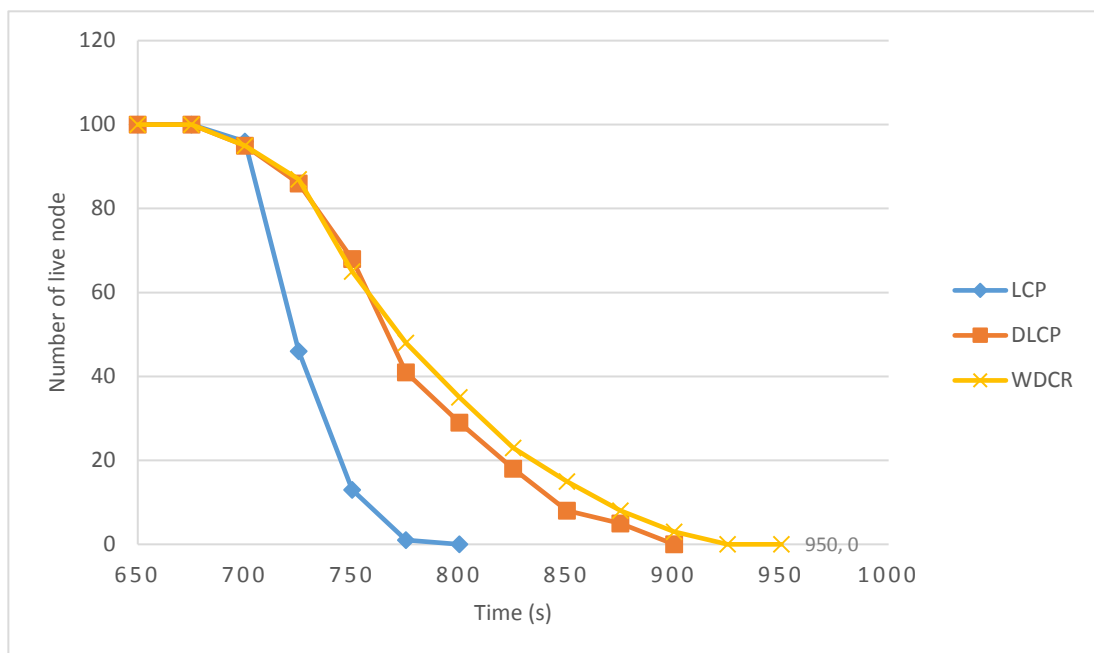
Figure 6.3. Number of live sensors vs numbers of rounds .

the LCP protocol was around 800 rounds and was 900 rounds in the DLCP protocol compared to 950 rounds in WDCR. Therefore, the new approach of selecting the CH saves additional energy by increasing the network lifetime by 6%.

6.4.3   Network Lifetime

To validate the performance of WDCR further, additional evaluations were conducted using different lifetime metrics FND, HND, and LND in relation to networks ranging from 100 to 350 nodes in size. The performance of WDCR is compared to LCP and DLCP protocols in all sets of network.

Figure 6.4 demonstrates the network lifetime up to when FND. In the network of 100 nodes, WDCR performs considerably better by 0.21% and 0.288% than LCP and DLCP respectively. However, when we increase the number of nodes the WDCR performance declines. In comparison with the other two protocols in their best performance in networks, DLCP outperforms WDCR by 0.20% in 250 nodes and LCP outperforms WDCR by 0.021% in 150 nodes. It is evident that the differences are only marginal.
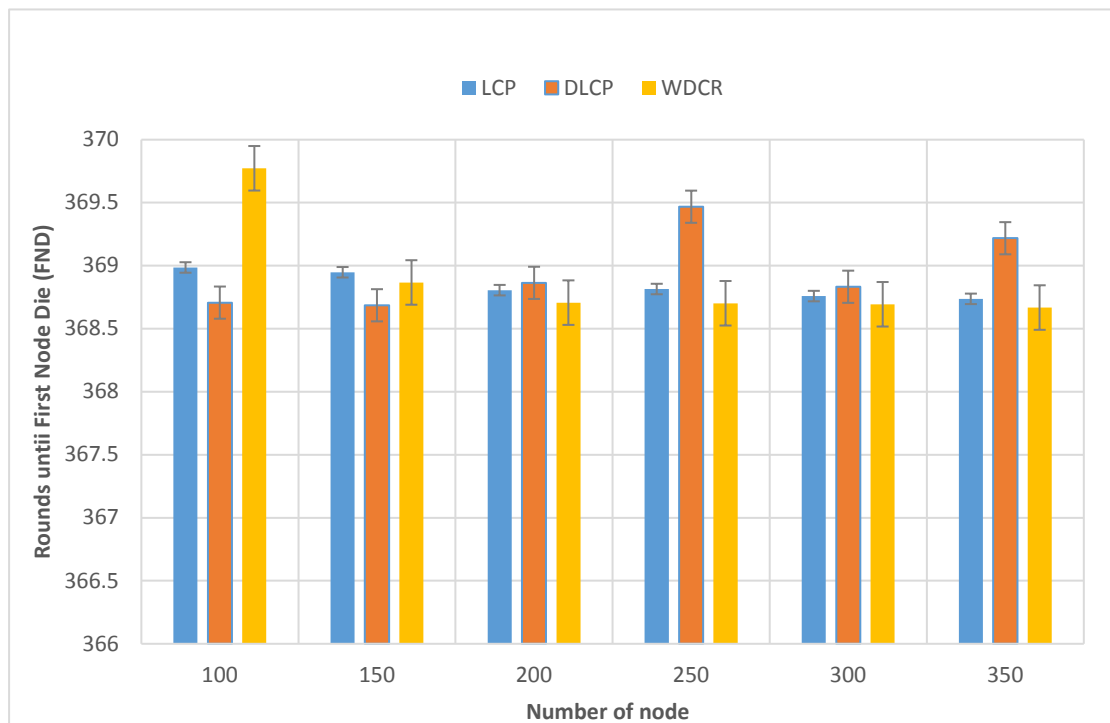
Figure 6.4.Network lifetimes up to the FND in LCP,
DLCP, and WDCR.

Figure 6.5 shows the number of rounds up to when HND in the network domain die. Similar to results in Figure 6.5. WDCR performs best in the network of 100 nodes by 4.46% and 3.02% than LCP and DLCP respectively. Comparable with the previous analysis, performer of WDCR declines when the number of nodes increases. In comparison with the other two protocols best performance in networks, DLCP outperforms WDCR by 13% at 200 nodes and LCP outperforms WDCR by 0.20% at150 nodes.
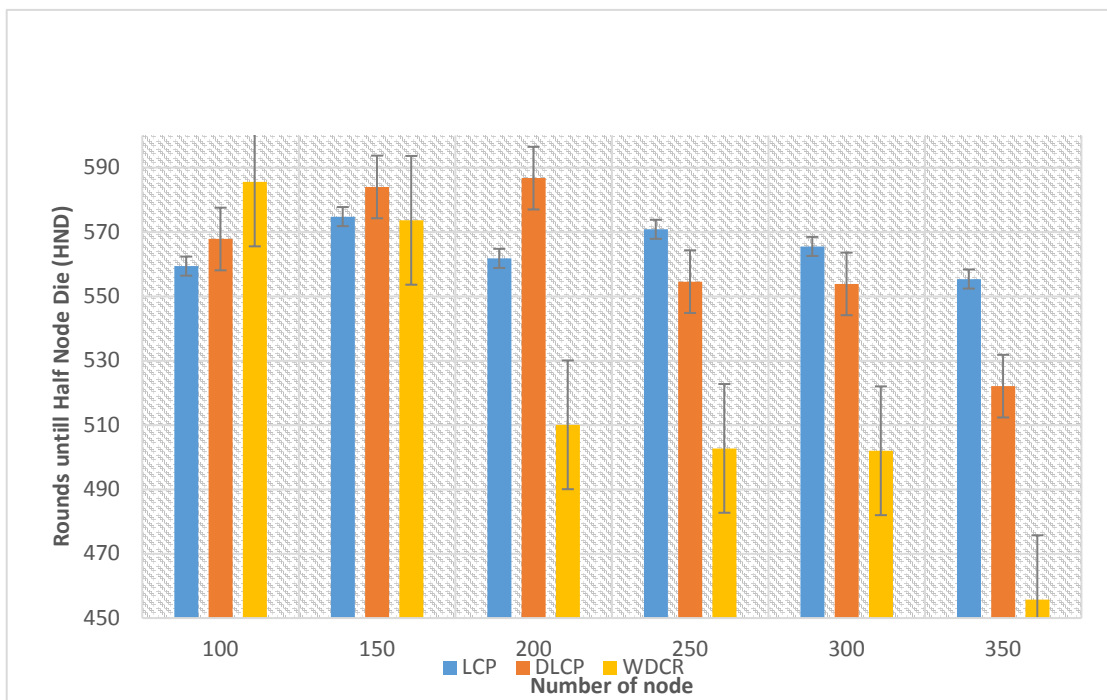
Figure 6.5. Network lifetime up to the HND in
LCP, DLCP, and WDCR.

The last metric of the lifetime performance is depicted in Figure 6.6, and it considers network time until the LND. The results are rather different from the two previous experiments. The WDCR performs better compared to its peers, regardless of the size of the network. The peak performance of the WDCR is recorded in a network size of 150 nodes, where it outperforms DLCP by 2.53% and LCP by 6.56%. In comparison with the other two protocols best performance in networks, WDCR is more efficient by 2.53% and by 1.03% than DLCP at 150 and LCP at 350 nodes respectively.
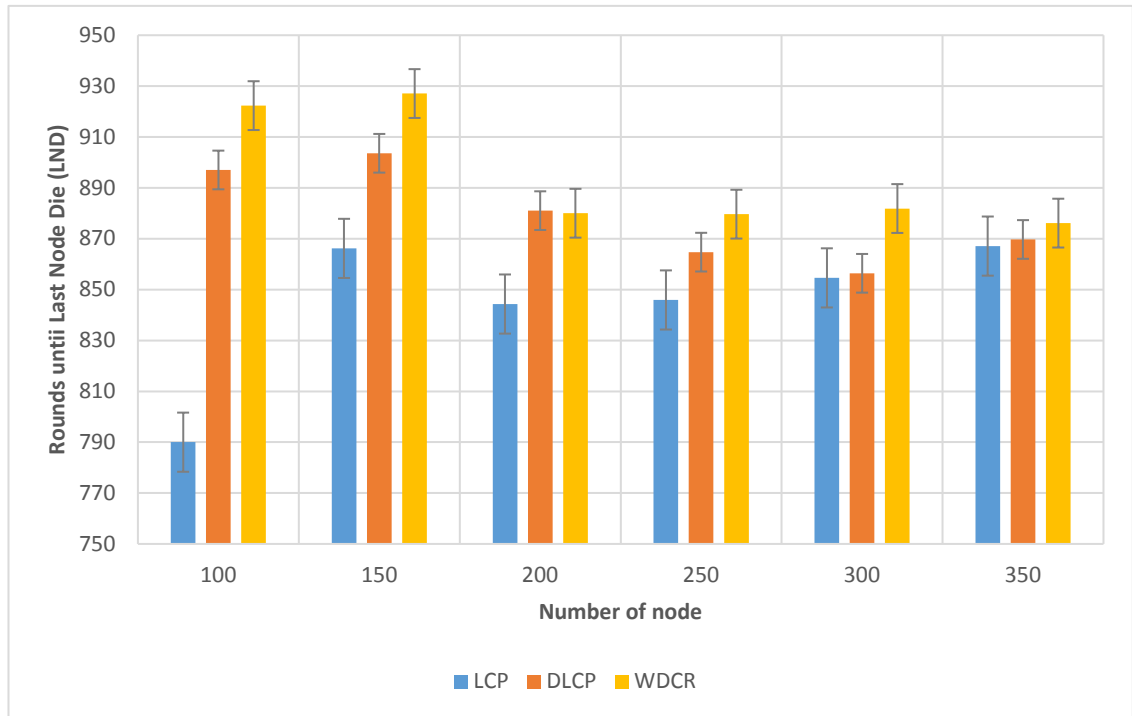
Figure 6.6. Network lifetimes up to the LND in
LCP, DLCP, and WDCR.

6.4.4   Delivered Data Messages

The quantity of delivered data messages per round, revealing similar results across all three protocols. Comparable quantity data is delivered by LCP, DLCP and WDCR from the beginning of the simulation until the end of the first round.

6.5   Conclusions

This chapter revisits the energy consumption problem in WSNs and proposes WDCR as a new energy-efficient routing protocol for WSNs. In WDCR, the selection of the CH is based on a combined weight metric that considers the following system parameters: remaining energy, CHF, and node distance to the BS. The results are compared to the results of the previously proposed protocols LCP and DLCP that only consider energy as the metrics for selection of a CH. Our results show a variation of results for WDCR performance.

When considering the reduction in energy consumption in the setup message overheads, WDCR performs better compared to LCP and marginally better than

DLCP. The WDCR has the lowest rate of setup messages with an average improvement of 8%. In the scenario of 100 nodes, the WDCR reduced energy consumption by 1.086 J (8.415%) when compared to LCP and by 0.57 J (5%) when compared to DLCP, consequently increasing the network lifetime by 6%. However, in the network lifetime evaluation based on the lifetime metrics of FND, HND, and LND, the WDCR performance is less convincing. In the FND and HND experiment, WDCR performs better only in the network of 100 nodes. In the larger networks, the performance of WDCR declines considerably. On the other hand, in the LND experiment, the WDCR performance is greater than the performance of LCP and DLCP, regardless of the size of the network. Additionally, the QoS is not compromised and remains almost equal in all three protocols.

Based on these results, it can be argued that, by using combining metrics for selection of the CH, the network performance in WDCR improves gradually and becomes more balanced over time. Further discussion of the experiment results and a comprehensive conclusion of these are presented in the following chapter.

Chapter 7

Conclusions and Future Work

7.1 Summary

Energy efficiency is one of the most important issues related to the use of WSNs. In general, WSNs are composed of a large number of SNs that can be randomly deployed indoors or outdoors, monitoring relevant factors in their environments [6]. The SNs are battery-operated; therefore, they have limited power and processing capabilities and are liable to failure. Such failures cause communication disruption and frequent network topology changes [21]. To address this issue, the research community and the industry have put a great deal of effort into designing energy-efficient routing protocols to prolong network lifetimes. Cluster-based routing protocols are considered to represent the most energy-efficient approach [24].

In this thesis, the ultimate goal was to contribute significantly to the advancement of WSN technology and, to this end, to propose methods for prolonging the lifetimes of systems while achieving the required QoS. In Chapter 1 the goal was set to address the current, known problems of cluster-based routing protocols. These were identified as follows: first, the consumption of unnecessary energy and time, which is related to the iterative clustering process; second, the extra energy waste due to the unequal distribution of the CHs; third, the selection of the CH based exclusively on a single metric.

In Chapter 2, a general review was conducted to identify the state-of-the-art developments in WSN technology, understand the structure of WSNs, comprehend the field of applications wherein wireless sensors can be used, review the wireless communication standards mechanisms, and examine the routing technologies used by WSNs.

In Chapter 3, energy efficient cluster-based routing approaches have been surveyed and the issue of clustering and clustering formation was discussed. This covers CH selection, how often the clusters must be re-created, the size of the clusters, and number of hops required for communication, and other issues regarding cluster communication describing how data are transferred across the network. This improved perception and awareness helped in discovering the problems inherent in current WSN clustering techniques and the possible solutions to these issues.

In Chapter 4, the justification for the most suitable simulation software for carrying out the experimental work was discussed. We selected Castalia as the most suitable simulation tool. It is the most appropriate both in terms of conducting the experiments and in terms of validating the results of the energy-efficient protocols. We compared the performance of Castalia to that of other simulators commonly used in WSN studies. The choice of simulator was based, in parallel, on the motive of the study, its level of complexity, cost considerations, the consistency of results, and the level of support offered within the WSN research community. The Castalia software was the most suitable simulator for the following reasons. First, it offers a modular simulation framework that allows the addition of extra functionalities through extensions. Second, it is open-source, which eliminates the extra cost that might

otherwise be incurred. Third, it is easy to comprehend and utilise. Last, it offers consistent and reliable results. In addition to the discussion regarding the choice of the most suitable simulation tool, Chapter 4 also included a discussion on ideal simulator scenarios. To evaluate and compare the performance of the proposed approaches and routing strategies in relation to energy consumption, the following primary simulation parameters were proposed: location of based station, size of sensor field, and size of network. Subsequently, to validate the proposed mechanisms in terms of network lifetimes, the following combination of metrics was proposed: setup message overhead, energy consumption, network lifetime, and delivered data messages. In Chapter four we have also proposed an original mechanism to manage the energy consumption in WSN. This mechanism has become the first contribution of this thesis. All the contribution of this thesis will be discussed in the following section.

7.2   Contributions

In this section, an indication is given of how the overall aim of this study have been achieved and to what extent the objectives were met.

7.2.1   Load-balancing Cluster based Protocol (LCP)

In Chapter 4, we proposed a new protocol LCP [133] to overcome the problem of high energy consumption by CHs during repeated fix-length rounds and to reduce the effects of early CH deaths on the operational phase. In LCP, the nodes are assumed to be randomly deployed across a large sensor field and be unaware of their location. The LCP is a fully distributed protocol whereby the nodes independently configure and form the network topology. In LCP, unlike conventional WSN cluster-based techniques, the cluster node with the maximum energy level is selected as the new CH before starting off a new round. The new round can only be initiated when one of the clusters completes the CH rotation task among all its CMs. As result, using this technique, we were able to reduce the overhead represented by the control message exchanges that need to take place during each round. LCP effectively balances the energy consumed across all SNs, reduces the overhead that occurs in each round and increases the network lifetime by 15% (over LEACH, HEED, and R-HEED).

7.2.2   Dynamic Load-balancing-aware-Protocol (DLCP)

The second contribution of this research, described in Chapter 5, was provided for by building upon and improving the LPC by proposing the DLCP [114]. This adaptive rotation time controller addresses the inequitable distribution of CH nodes within a network. This inequitable distribution can cause increased energy waste. The DLCP protocol divides the node clusters into groups according to sizes and provides a predefined interval timer at the beginning of each round for selecting the CH. This action reduces the frequency at which the re-clustering message will be triggered by the BS. The CHs continue to rotate the leadership among the same CMs by electing the node with the highest residual energy in each round. When the energy of one CH falls below a fixed threshold CH (T_{CH}), a new clustering process will be initiated. The results show that DLCP increases network lifetime by 10% (over EEUC and HEED).

7.2.3   Weight-Driven Cluster Head Rotation (WDCR)

In Chapter 6, the third contribution of this thesis is shown to be fulfilled by introducing the WDCR protocol [152]. This protocol selects the CH based on an original combination of parameters, which has not previously been considered. First, the WDCR selects the CH based on the following factors: residual energy, distance of the node from the BS, and the number of times the node has been selected as a CH. Second, the weight of the node is calculated based on these three factors, and the node with the highest weight is selected as a CH. Third, as in DLCP, unequal-size clusters are formed and an intra-CH rotation is applied. The WDCR performance results were compared to those of LCP and DLCP. The results demonstrate that WDCR increases the network lifetime by 6% (over LCP and DLCP).

Finally, this thesis has accomplished all its aims, as declared in Chapter 1. Equally, the proposed contributions were made, and the research questions answered. Our analysis indicates that the proposed approaches balance the energy consumption very well across all the SNs and achieve obvious improvements in terms of network lifetimes. Although the quality of the service was not directly measured, the results show that the delivered data messages were not compromised.

7.3   Future Work

While the schemes developed in this thesis would seem to result in substantial enhancements in terms of energy efficiency and network lifetimes, we believe that there are still ways to increase network performance. The following areas can be considered as future research directions that can be taken.

1. Investigate the performance of developed schemes with respect to other networking metrics such as network overhead, packet delivery ratio and end to-end delay under different operating conditions.

2. The development of weighted clustering algorithms could concentrate on cluster formation and CH election methods, which can create more stable network structures incurring less energy cost. Several parameters, such as transmission range, number of neighbours, degree differences, remaining battery power, and distances to neighbours might play a significant role in the process of selecting CHs and clustering formations.

3. An efficient threshold could be determined for use in terms of node energy and cluster sizes. This could be achieve by decreasing the number of re-clustering processes required across the network domain. Using alternative parameters for calculating the combined weight (of a possible CH) may help to balance CH loads and consequently decrease general overheads within the network.

4. The success of the proposed energy efficient management approaches has been assessed entirely in relation to self-organising methods. Thus, investigating the consequences of applying these techniques to centralised clustering schemes would be a considerable path for future research.

5. Node mobility can be considered and improved routing protocols can be derived to enhance the current energy saving protocols.

6. Implement the proposed approaches on real test beds in order to compare the obtained results with analytical evaluations.

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