Routing and Medium Access Control (MAC) in Wireless Sensor Network for Monitoring Emergency Applications

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by

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Abstract

In recent years, Wireless Sensor Networks (WSNs) have been implemented in many applications including emergency applications. Emergency applications require different characteristics than others, such as robust communication, low energy consumption and minimum end-to-end delay. Routing and Medium Access Control (MAC) are two protocols that have been used by many researchers to achieve those requirements. This thesis mainly focuses on studying distributive clustering routing and MAC protocol for emergency applications.

To design robust communication in emergency applications, this thesis has proposed a modified LEACH protocol considering the health status of sensor nodes. LEACH is a benchmark protocol employing distributive clustering-based routing with low energy consumption, however this protocol is not suitable for emergency applications. The health status refers to the condition of nodes, safe or in danger, with the danger status shows the high probability to be destroyed sooner because of external factors such as fire. The proposed approach avoids selecting the nodes in danger as cluster heads. Furthermore, efficient multi-hop communication is employed to minimise energy consumption. The simulation result shows that total data received, energy consumption , packet delivery ratio, and energy efficiency of the proposed approach are stable with an increasing number of destroyed nodes.

Furthermore, a grid-based clustering approach with health status is proposed to further enhance energy constraint and robust communication. The proposed approach includes distributive clustering and incorporate constant number of CHs in every round. The remaining energy, the health status of node, and the distance to the centre of the grid are consided when choosing the cluster head. Simulation results have revealed that the proposed protocol has a significant effect on the time for first node to destroy due to energy consumption, an increase of 45% compared to LEACH. Furthermore, packet delivery ratio of the proposed approach is enhanced by 16% compared to LEACH.

In order to reduce end to end delay, a priority-based grid Time Division Multiple Access (TDMA) has been proposed. In this approach, traffic is classified into two categories: emergency traffic from danger nodes, and monitoring traffic from safe nodes. This scheme was implemented using three steps: formation of a new TDMA frame, the arrangement of slots and priority allocation. Simulations results showed an improvement of around 65% and 70% in end to end delay compared to Grid and LEACH approaches.

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Table of Contents

References

List of Figures

List of Tables

List of Abbreviations

ADC	Analog to Digital Converter
APTEEN	Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network
BMA-MAC	Bit-map-assisted Medium Access Control
BS	Base Station
B-MAC	Barkeley MAC
CH	Cluster Head
CM	Cluster Member
CPU	Control Processing Unit
CSMA-CA	Carrier Sense Multiple Access Collision Avoidance
D-MAC	Data gathering tree-based MAC
DARPA	Defence Advanced Research Projects Agency
DS-SS	Direct-Sequence Spread-Spectrum
DSN	Distributed Sensor Networks
E-TDMA	Energy Time Division Multiple Access
EFMP	Energy-efficient Fire Monitoring Protocol
EMA	Environmental Monitoring Aware
ETX	Expected Transmission Count
FND	First Node Destroys
HEEMAC	Hierarchical Energy Efficiency Medium Access Control
HND	Half Node Destroys
HT	Hard Threshold
IPL	Instability Period
ISA	International Society of Automation
IT	Information Technology
IWSN	Industrial Wireless Sensor Network
LEACH	Low Energy Adaptive Clustering Hierarchical
LND	Last Node Destroys

LTA	Long-Term Application
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MTA	Medium-Term Application
MUP	Maximise Unsafe Path
NFC	Near Field Communication
NS2	Network Simulator 2
PDR	Packet Delivery Ratio
QoS	Quality of Service
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
S-MAC	Sensor MAC
SS-MAC	Slot Stealing Medium Access Control
SPIN	Information via Negotiation
ST	Hard Threshold
STA	Short-Term Application
TEEN	Threshold sensitive Energy Efficient sensor Network
TDMA	Time Division Multiple Access
WASN	Wireless Active Sensor Node
WINS	Wireless Integrated Network Sensors
WMSN	Wireless Multimedia Sensor Network
WPSN	Wireless Passive Sensor Node
WSN	Wireless Sensor Network
WPAN	Wireless Personal Area Network
Z-MAC	Zebra MAC

List of Publications

Published Conference Papers

- A. Anhar, R. Nilavalan, and M. S. Iqbal, "Clustering Based on the Node Health Status in Wireless Sensor Networks," in Proc. Of 11th International Conference on Telecommunication Systems Services and Applications (TSSA), Lombok, Indonesia, 26-27 Oct. 2017. (Published in IEEEXplore http://ieeexplore.ieee.org/document/8272910/)
- A. Anhar, and R. Nilavalan, "Multi-hop Hierarchical Routing Based on the Node Health Status in Wireless Sensor Network," in Computing Conference 2018, London, UK, 10-12 July 2018.
- A. Anhar, R. Nilavalan, and F. Ujang, "A Survey on Medium Access Control (MAC) for Clustering Wireless Sensor Network", in 2nd International Conference on Electrical Enggineering and Informatics, 16-17 October 2018.

Chapter 1: Introduction

1.1 General Background

The popularity of Wireless Sensor Network (WSN) within research and industry communities has increased in this decade. Many studies have been conducted to enhance the performance of WSN. There have been a lot of proposed approaches focusing on the physical layer and Medium Access Control of WSN, as reported by [1]. Furthermore, as presented in [2], researchers have also contributed to improving routing protocol in WSN, a part of the network layer. In the early stage, they have developed a mathematical or simulation model of WSN to analyse their proposed approaches. Today, testbeds, which are real sensor nodes designed for experimentation, are applied to study WSN in practical implementations. According to [3], more than 30 testbeds have been developed by many university research groups. In the era of Industry 4.0, WSN has a vital role in promoting smart factories and intelligent manufacturing systems[4]. With the massive number of WSN applications, there has been an increase in the forecast of the WSN market from $0.45 billion in 2012 to $2 billion in 2022[5].

In general, there are two main advancement technologies contributing to the development of WSN: sensor technology and wireless communication [6]. A new generation of sensor technologies has become smaller, low-cost, and reliable[7]. Nowadays, an ultrasonic sensor can have the dimensions 3.5mm x 3.5mm, which is claimed to be the most miniature sensor in the world[8]. Accuracy and low power are other benefits delivered from this sensor. Wireless technology offers numerous advantages such as mobility, flexibility, and lack of wiring[4]. Indeed, there has been an increase in the bit rate of wireless communications over the year. The minimum bit rate of 5G, which is the latest generation of wireless network, is 1 Gbps or ten times of 4G[9]. These beneficial factors have stimulated WSN into a new era of the Internet of Things (IoT)[7], [10].

WSN differs from other wireless networks such as Mobile Ad Hoc Network (MANET) in different ways. Although both systems have limited energy resources, network lifetime of WSN is strict since the difficulty in recharging or replacing WSN's batteries. Terminals in MANET such as a laptop or mobile phone are more powerful than sensor nodes which are supplied by only AA or AAA batteries[11]. Moreover, traffic in WSN is generated by sensors as interaction with the environment, not human interaction such as MANET. This characteristic traffic can embrace a long time scale monitoring but can be very bursty traffic when something happens (in emergency applications)[12]. On the other hand, voice, text, and video are common traffic delivered in MANET. In connection with scalability, nodes in WSN can reach thousands or perhaps hundreds of thousands of entities owing to a wide area monitored. Some well-known examples of WSN applications needing high scalability are precision agriculture, forest fire monitoring, intelligent warehousing, and wildlife habitat monitoring[10]. Lastly, since WSN has a broad area implementation, there is a wide diversity of requirements for every application[13]–[15]. In medical applications, for example, the essential elements are security and network reliability while environmental monitoring applications only require robust and energy efficient.

Wireless Sensor Network (WSN) has changed our daily life activities nowadays. It has been applied in many application areas including environmental, healthcare, military, industry, transportation, and other domains[7], [16]. Applications of WSN in the telehealthcare system in rural areas has given an easiness in monitoring the patient's activity continuously against the vital signs of disease and sending the immediate alert for emergency response[17], [18].

Among applications of WSN, emergency applications have several contributions to the sustainability of human life and earth ecology. The natural disasters such as tsunami, forest fire, earthquake, and volcano, have occurred recently all around the world and these have led to the loss of a significant number of human life and properties. Forest fire, for instance, causes the emission of carbon dioxide (CO2), haze and other greenhouse gases. There is an increasing number of burnt areas, and it is estimated between 300 and 400 million hectares per years[19]. Another well-known disaster is the Indian Ocean tsunami generated by the Sumatra-Andaman earthquake of 26 December 2004. About 350.000

people have destroyd, and the Aceh province of Indonesia is the worst land damage owing to the closest to the epicentre of the earthquake[20]. Furthermore, the total cost in Aceh estimated by the World Bank is approximately US$4.45 with 78% of damage comes from private sectors. Thus, the detection and monitoring system for disaster situations bring a high number of merits and WSN is the best solution instead of satellite technology and digital camera system[21].

1.2 Motivation

As stated in section 1.1, every WSN application possesses different characteristics which bring unique approaches in the system design. In emergency applications, for example, there is an opportunity that sensor nodes are disconnected or even destroyed as the disaster expands throughout the location of those nodes. Since sensing data from surrounding disaster area are important, the links between these nodes and a sink should not collapse. Thus, robust communication in emergency applications is a prerequisite to avoid faults in handling emergency situations. With regard to latency, emergency applications have to accommodate emergency packets when sensor nodes detect emergency data. In other words, there exists a high priority for emergency packets, and they are allocated in specific slots to minimise end-to-end delay in the network. Furthermore, this approach can evade collisions among packets and guarantee a specific delay for emergency packets.

For all applications, a crucial issue that must be handled in WSN is energy constraint[22][23]. A study in [24] has confirmed that the significant amount of energy get wasted in a sensor node due to radio communication. This is related to transmitting and receiving packets throughout the network. As the number of packets sent goes up, energy consumed rises accordingly. Moreover, a packet size and transmission distance influence energy expenditure. In wireless media, before sending data to the sink, generally, a node performs sensing the medium to avoid collisions among packets in a shared medium. Retransmission packets due to collisions as well as sensing activities reduce the energy of the node.

A considerable number of approaches have been proposed to overcome WSN limitations, involving physical to the application layer. A routing protocol, which is a method to route packets from a source to a destination effectively, has been used to overcome WSN issues, but most of them focus on energy saving. In fact, routing protocol can be optimised to enhance not only energy efficiency but also end-to-end delay since it can reduce the number of transmissions in the network. Moreover, safe routes can be performed by an effective routing in disaster situations in order to avoid link failures because of burnt or destroyed nodes. Hence, the performance of WSN for emergency applications can be improved by an optimal routing protocol.

Another important algorithm which can significantly influence the performances of WSNs in many perspectives is the Medium Access Control (MAC), part of Link Layer protocol. MAC directly controls activities of the communication module, including sensing, reception, and the transmission process[25]. Moreover, a flexible and dynamic MAC can reduce the medium access delay by minimising collisions and growing reliability by minimising traffic losses[26]. Since delay constraint is one of the issues in emergency applications, improving MAC can be an excellent approach to enhance the performance of WSN in emergency applications.

Low Energy Adaptive Clustering Hierarchy (LEACH) proposed by Heinzelman in [27] is a protocol architecture for WSN to achieve energy efficiency by performing a distributed clustering algorithm and aggregation. It is a well-known distributed routing and many proposed approaches are developed from LEACH[28], [29]. Since LEACH assumed that sensor nodes always have data to be sent to the sink, this approach is suitable for monitoring applications[30]. Nevertheless, LEACH is not designed to accommodate different types of traffic. As a result, applications containing different types of traffic, such as emergency traffic, cannot be delivered with a better performance. Moreover, there is no mechanism to minimise end to end delay of traffic in the network, and therefore, the lower delay for specific traffic cannot be achieved. Although LEACH has established the optimal number of Cluster Head (CH) is five percent of total sensor nodes, it fails to maintenance this optimal number of CH. Energy efficiency of network can be optimised by clustering sensor nodes in the optimal value. These lead to a motivation to investigate the potential of modifying LEACH to accommodate different type of traffic and enhance its energy efficiency in monitoring emergency applications.

1.3 Aim and Objectives

Having developed issues that have to be considered in emergency applications, the main aim of this study is to contribute to enhancing performance of WSN for monitoring emergency applications by designing an effective routing and Medium Access Control protocol. To address the aim of this research, the following objectives are established:

1. To understand the current adoption of the routing and MAC protocol in WSN for emergency applications.
2. To study the effect of a node failure in emergency applications on WSN performance.
3. To investigate the use of standard LEACH routing protocol considering node failures.
4. To develop an energy efficient routing protocol based on a grid clustering.
5. To develop energy efficient and low latency MAC protocol considering node failure.

1.4 Author’s Research Contributions

This thesis contributes to the knowledge by designing and developing routing and Medium Access Control (MAC) Wireless Sensor Network for monitoring emergency applications. The contribution can be categorised as follow:

1. A new modified LEACH protocol considering the health status of the node is proposed to enhance network reliability for emergency applications. The health status of the node is introduced, and it refers to the condition of the node, whether

danger or safe. A danger node has a probability of dying sooner because of external sources, such as fire or earthquake. The proposed approach avoids choosing a danger node as a cluster head to degrade many lost data. Moreover, it applies multi-hop communication based on the distance to diminish energy consumption and increase the scalability of sensor nodes. This approach has been presented in two different conferences in [13] and [31].

2. A new grid-based clustering is proposed to enhance the energy efficiency of the network. Unlike LEACH, the approach has an optimal constant total CH in every round. It is a distributive clustering, and a CH is selected based on remaining energy, distance to the centre of the grid, and the health status of the node. The algorithm in the first round is different than other rounds, and the CH in the previous round chooses the CH in the current round.
3. A new priority-based Time Division Multiple Access (TDMA) scheme for monitoring emergency applications is proposed. The approach aims to reduce average end-to-end delay as well as energy consumption for clustering network. Traffic is classified into two classifications: emergency and non-emergency traffic. A new TDMA frame is introduced according to this classification. Moreover, it applies a priority for emergency traffic by assigning slots of emergency traffic at the beginning of the frame. Then, these slots are sent directly from the CH to the Base Station (BS) without aggregation.

1.5 Thesis Organisation

There are six chapters in this thesis, of which this is the first. Chapter 2 provides a background description of WSN, covering elements, network topologies, standards, and applications of WSN. Additionally, this chapter offers in-depth coverage of routing and MAC protocol, including their definitions, characteristics, and taxonomies.

Chapter 3 describes a well-known cluster based routing scheme, LEACH. Here, the concept of the node health's status related to emergency applications is defined. Some related works are explored. Afterwards, a modified LEACH is described and compared with LEACH and LEACH-C using Network Simulator 2.

Chapter 4 focuses on developing a grid-based clustering. After exploring some existing grid clustering methods, a new distributed grid clustering approach is introduced. In the end, the simulation model and the comparative study of the proposed model and LEACH have been presented in detail.

Chapter 5 explores issues in MAC for clustering WSN. Having discussed the related work, a simple MAC for clustering WSN considering energy as well as packet priority for emergency applications is proposed. This proposed approach then is compared with other MACs for clustering network.

Finally, chapter 6 concludes the thesis by discussing contributions to the theory and practise. This chapter ends by identifying some limitations and possible future works.

Chapter 2: An Overview of Wireless Sensor Network

2.1 Introduction

After presenting the background, motivation, scope of the research, this chapter reviews the Wireless Sensor Network technology, along with its some protocols. This chapter is divided into five main sections. Section 2.2 explores the background of WSN technology. Two main elements of WSN are discussed in this section. Following this, some groups of WSN's topology are presented. WSN's topology also plays an essential role in enhancing its performance. The base standard of WSN is introduced in this section including some development standards which are suitable for WSN requirements. As a network, WSN has some performance metrics showing its quality, and this also presents in this section. A considerable number of WSN applications along with their taxonomies and requirements is the last part of section 2.2. Improving energy efficiency and latency in WSN can be done by an effective routing protocol. There are many types of WSN routing with different characteristics. Therefore, section 2.3 discusses how routing can enhance WSN performance and classifies routing according to the previous surveys. MAC as another approach to tackle limitations in WSN is presented in section 2.4. After exploring factors influencing in designing a useful MAC, this section also offers some taxonomies of MAC in different perspectives. The last section describes energy models that have been implemented in WSN environment. The energy model is an essential part of calculating energy consumed. Furthermore, section 2.5 presents the parameters and assumptions used in developing the energy models.

2.2 Wireless Sensor Network (WSN)

The first history of the WSN technology begun in around 1980s when the United States Defence Advanced Research Projects Agency (DARPA) for military applications initiated Distributed Sensor Networks (DSN) program. Following this, in 1993 DARPA continued its research in WSN through a Wireless Integrated Network Sensors (WINS) program[7], [32]. As the development of wireless and sensor technologies has increased recently, WSN has gained popularity, and the spread of its implementations reaches all area of our life.

In spite of a lot of functions from WSN implementations, the main task of WSN is to sense and collect data, process and send it to a sink or a base station (BS)[33]. Data sensed from the environment can be the physical world, a biological system, or an information technology (IT) framework. Data collected in the BS can be transmitted to the internet to expand its connectivity. Figure 2-1 shows the architecture of WSN[11].

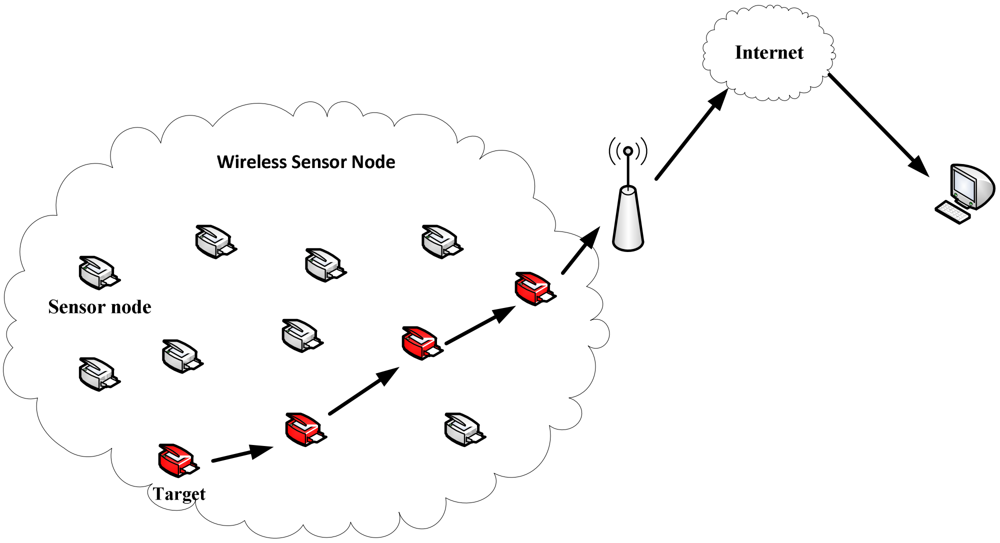

Figure 2-1. Simple architecture of WSN[11].

In literature, WSN terminology nowadays can be combined with other words. Authors in [34] introduced the concept of Wireless Multimedia Sensor Network (WMSN). Nodes in WMSN are equipped with multimedia sensors such as CMOS cameras and microphones, which are sensing multimedia contents from the environment. WMSN can be implemented in many areas, including multi-cameras surveillance, visual target tracking, location-based multimedia services, and situation awareness[35]. These various applications will enhance WSN capability.

WSN play an important role in the Industry 4.0 era. A new paradigm Industrial Wireless Sensor Network (IWSN) has been attracting the intention of industries, researchers, and governments[4]. Implementation of IWSN is a challenging task since it is different from WSN technology in terms of mobility, topology, channel interference, security and error tolerance.

In connection with deployment's areas, WSN can be classified into terrestrial, underground, and underwater WSN[36]. A hundred or more sensor nodes scattered in the land area perform a terrestrial WSN. These inexpensive sensors can be deployed randomly or pre-assigned manner. On the other hand, sensor nodes in underground and underwater WSN are expensive. Underground sensor nodes usually deploy in caves or mine to monitor underground conditions while sensors in underwater WSN communicate each other's using acoustic waves, and they are laid out underwater.

Works in [37], [38] also introduced a new terminology of WSN: Wireless Active Sensor Node (WASN) and Wireless Passive Sensor Node (WPSN). Both these terminologies are related to the way of power supply in a sensor node. External sources such as batteries are implemented in WASN while WPSN is supplied by an external Radio Frequency (RF) sources. To maintain energy sustainability when RF source cannot provide enough energy, WPSN is equipped with a supercapacitor.

2.2.1 Elements of WSN

Despite different terminologies of WSN as described in section 2.2, there are only two main elements of WSN: a sensor node and a base station (BS). This subsection will explore these elements.

a. Sensor node

A sensor node in WSN is a part that performs three main activities covering sensing, processing, and sending data to the destination. Therefore, there are four modules in sensor node to accomplish those process: a detecting module, a processing module, a communication or transceiver module, and a power module which is responsible for supplying energy to other components[11], [33], [39]. A block diagram of a sensor node can be found in Figure 2-2.

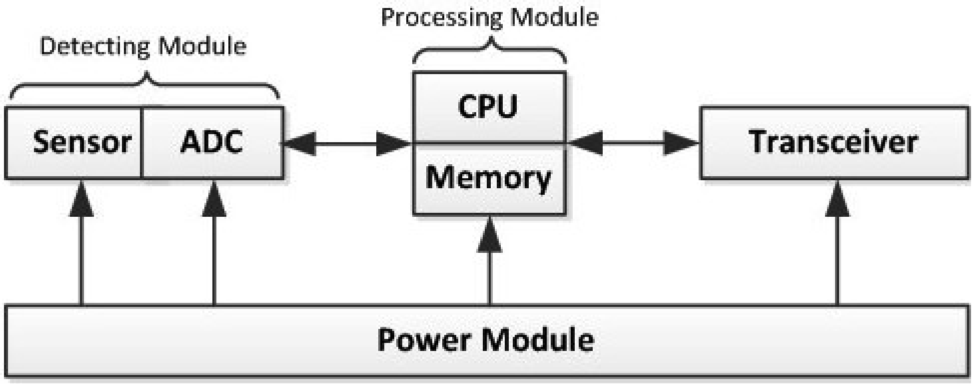

Figure 2-2. Four main modules in a sensor node.

A detecting module is a part sensing environment's parameters, covering three main aspects: physical (radiation level, fog, dust, etc.), chemical & biological (concentration of a substance or agent at specified concentration levels) and event measurements (tracking events). Size, cost, robust, and sensitivity are some influential factors in choosing a sensor. Moreover, an Analog to Digital Converter (ADC) in this part is used to convert the analogue signal to the digital domain. To process the signal from ADC, microprocessor, microcontroller, or field-programmable arrays are generally utilised as a Control Processing Unit (CPU). The processing unit also needs memory to save its data and performs the computational processes such as aggregation. A transceiver, a module consuming a lot of energy, performs wireless communication among sensor nodes including transmitting and receiving packets. A last part is a power unit supplying energy to all other modules. Since batteries are supplied as the power unit, their energy efficiency must be high to prolong their lifetime. If WSN is implemented in a rural area such as forest fire monitoring, recharging these batteries are an unfeasible task.

b. Base station

Another element controlling the overall system of WSN is a base station (BS) or a gateway. It receives and processes data from sensor nodes, then sends data to the information management system. To perform these tasks, the BS is equipped with a communication module, a processing module, a human interface, and a power module. Unlike sensor node having energy constraint, generally, the power module in the BS can be a power supply, batteries, or both of that with unlimited energy. In centralised communication, a link communication controlled by the BS, the BS has a vital function in routing packets of sensor nodes. Here, the processing module is more complicated than in a standard BS which cannot control the network.

2.2.2 Network Topologies of WSN

WSN is a collection of sensor nodes connected to each other's by links to sense, process, and collect data to the BS. When the connection is represented as a geometric relationship of all link and sensor nodes, it is called as network topology[40]. Network topology influences how data can be delivered from sensor nodes to the BS. The network topology of WSN can be organised into three groups: clustering, mesh, and mixed topology.

- Clustering or hierarchical topology. This topology groups sensor nodes into clusters according to some criteria, such the distance, energy, etc. There is a cluster head (CH) in every cluster, and it chooses in the cluster formation phase. Other sensor nodes are termed a cluster member (CM). The CM in the same cluster performs a star topology in which data from the CM are sent to the CH. The CH aggregates data and forwards them to the BS. Figure 2-3 displays clustering or hierarchical topology which consist of two clusters. A star topology has an equivalent structure with this topology.
- Mesh or flat topology. In the mesh topology, all sensor nodes have the same capability to transfer data, and only can interacts with neighbouring nodes[34].

The simplicity is the main advantage of this topology since there is no cluster formation such as in the clustering topology. However, this topology lacks scalability, and as a result, it is not suitable implemented in the broad area monitoring. Figure 2-4 presents a network with mesh or flat topology. Here, data are travelled from node 1 to the BS via node 2 and node three because node 1 cannot communicate directly to the BS.

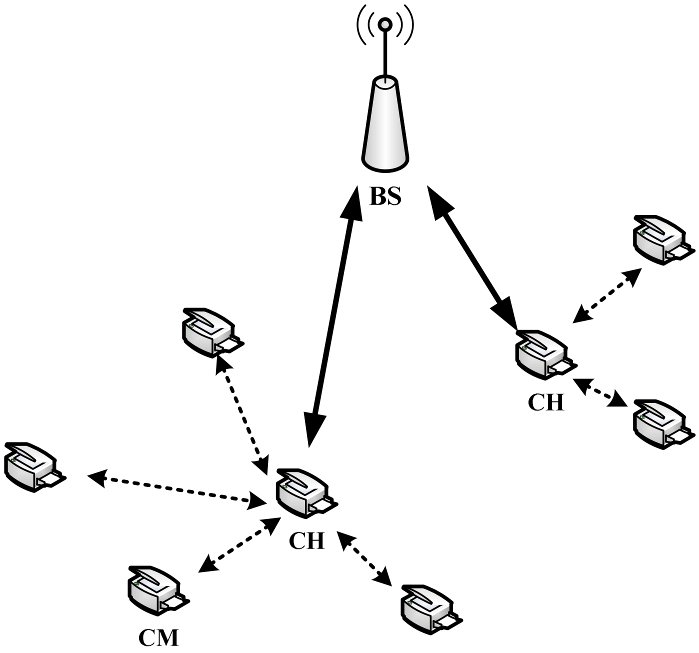

Figure 2-3. Clustering topology in WSN.

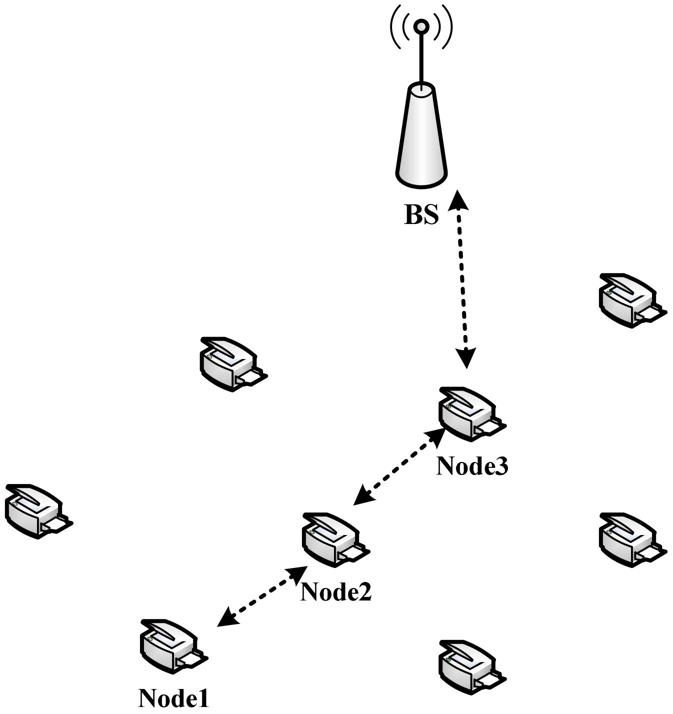

Figure 2-4. Flat or mesh topology in WSN.

- Mixed topology. As shown in Figure 2-5, this network is a combination of clustering and flat topology. Data from CM are sent to the CH to perform aggregation. In this example, CM in cluster 1 sends its data to the CH1. CH1 transmit to a higher level of clusters, such as CH3 and CH4. CH4 also collects data from CH2 before forwarding all data to the BS. This topology offers high scalability due to multi-level clustering or hierarchy. Clustering formation is more complicated than a simple clustering topology since not only does this network define CHs but also it classifies them into levels according to their function in the system.

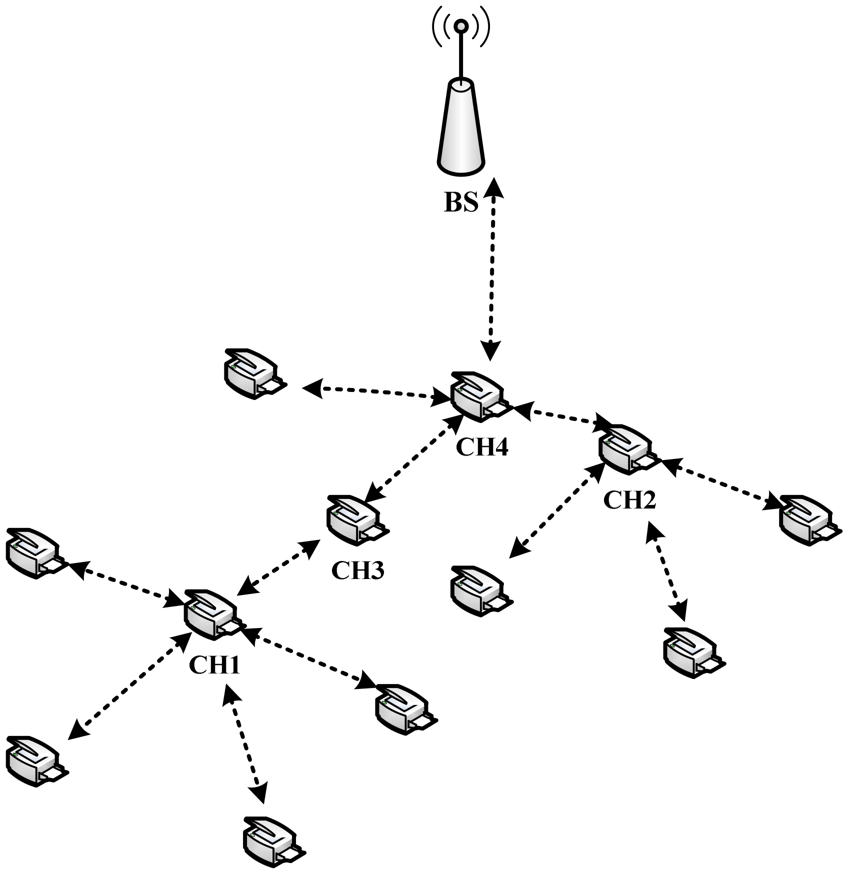

Figure 2-5. Mixed topology in WSN.

2.2.3 Wireless Communication Standards of WSN

As stated in subsection 2.2.1, both nodes and the BS as elements of WSN are equipped with a wireless module. The module performing sending and receiving packets from other nodes needs a standard to communicate with other networks[36]. This standard defines the functions and protocols required as an interface with a variety of networks. Also, the choice of standard in WSN is essential since every standard is equipped with different radio characteristics, and it must be fitted with WSN applications[5].

Usually, WSN follows the standard for Low Rate Wireless Personal Area Network (LR-WPAN) which has a low rate transmission and power communication. IEEE 802.15.4 is the primary standard focusing on those features. Moreover, this standard is suitable for short-range communications to minimise energy deplete. Basically, the standard defines the physical and Medium Access Control (MAC) layer characteristic for WPAN. It works on 868/915 MHz low bands and 2.4 GHz high bands, all using the Direct Sequence Spread Spectrum access method[41]. Carrier Sense Multiple Access Collision Avoidance (CSMA-CA) is a type of MAC utilised in this standard. Furthermore, the standard also supports two types of networks: clustering/star and flat/mesh topology[36].

ZigBee [36][41] is another suitable standard for WSN devices built on IEEE 802.15.4. It defines the higher layer communication protocols and supports many topologies including clustering, mesh, and mixed network with a maximum data rate of 250 kbps. It consists of three main devices: a Zig-Bee coordinator, a ZigBee router, and a ZigBee end device. The initiation of network formation is done by the Zig-Bee coordinator as well as bridging network together while multi-hop communication is performed by the ZigBee router. The ZigBee end device senses data from the environment and transmits only to the ZigBee router.

Another standard for WSN is Wireless HART, which is designed for industrial applications. It was released in 2007 and is based on 802.15.4. It operates on an unlicensed frequency of 2.4 GHz with 15 different channels[42]. WirelessHART is plotted to support clustering and mesh network with many features such as reliability, security, energy efficiency, and compatibility with existing devices[5]. There are five components in the

WirelessHART network: wireless field devices, gateways, process automation controllers, host applications, and network manager[36].

The ISA100 standards committee from the International Society of Automation (ISA) organisation established ISA100.11 standard for automation applications using WSN. Like WirelessHART, this standard applies 2.4 GHz with channel hopping to reduce interference and supports mesh as well as clustering network topology. It is compatible with IPv6 and existing standard such as WirelessHART[5]. ISA100.11a also provides scalable security functionality and low energy consumption.

The technology that supports a long distance communication for WSN applications is Long-Range Wide Area Network (LoRaWAN)[14][43]. In an urban area, this technology can reach 2-5 Km, while it can be 15 Km distance in a suburban area. Its network lifetime is around ten years with low power communication and data rate 27 kb/s or 50 kb/s. It operates on three band frequencies depend on the region, which are 433 MHz, 868 MHz, and 915 MHz. LoRaWAN consists of a sensor node, a gateway, and a network server. The gateway forwards data from the sensor nodes to the network server using a single-hop communication. This technology supports star-to-star topology between the sensor nodes to the gateway.

To compare clearly those WSN standards, Table 2-1 presents some physical features of ZigBee, WirelessHART, ISA100.11, and LoRaWAN standard[4], [5], [14], [36], [42]. Factors characterised by table 2.1 such as frequency, data rate, network topology and range of communication can be a guide in choosing a WSN standard.

Table 2-1. The comparison of ZigBee, WirelessHART, ISA100.11, and LoRaWAN.

Features	ZigBee	WirelessHART	ISA100.11	LoRaWAN
Frequency (MHz)	2400, 915, 868	2400	2400	433, 868, 915
Data rates (kbps)	Up to 250	Up to 250	Up to 250	Up to 50
Network Topology	Clustering/Mesh /Mixed	Clustering/Mesh /Mixed	Clustering/Mesh	Clustering/Star
Range (m)	10-100	1-100	1-100	2000-15000

2.2.4 Quality of Service (QoS) of WSN

Like other networks, WSN has a set of performance parameters showing its network quality. These parameters, which is known as Quality of Service (QoS), play an essential role in designing the WSN system. Some QoS parameters are listed as follow[44]:

1. Energy consumption: Since a sensor node in WSN is powered by limited energy resources, energy constraint is the central issue in WSN. Therefore, the first QoS parameter that always is used by researchers to compare its proposed approaches is energy consumption. At least, two perspectives in defining the energy consumption are available. Authors in [45] determine energy consumption as the total energy exhausted by all sensor nodes to send, receive, and aggregate data. This definition is accurate and also used by many studies such as [46][47]. Other definition such as total energy dissipation, which has the same meaning as the energy consumption, is used by [48]. The contrary meaning of the total energy consumed is the total remaining energy and works in [49][50] analysed their proposed approach with this metric.
2. Network lifetime: There are different definitions of network lifetime. Generally, it refers to the time when the first node completely exhausted its energy, or when a certain fraction of the network's nodes are dead, or even when all nodes are dead[32]. On the other hand, many studies in [50]–[57] use duration for First Node Destroys, Half Node Destroys, and Last Node Destroys as network lifetime when comparing their proposed approaches. Network lifetime also can be related to the number of alive nodes or the number of the dead nodes. Authors in [48]–[50], [54], [58]–[60] analysed their proposed approaches with others using the number of alive nodes over time or round while works in [45] used the number of dead nodes over rounds.
3. Delay: Regarding characteristics in emergency applications such as fire detection, delay is an important criterion to measure its performance. Works in [61][62] define that delay, which is commonly calculated on the average value, is period from a packet in the source until it reaches in the destination. Meanwhile, end-to-

end delay refers to the average delay, which is the total delay divided by the total number of packet received at the sink[46][63].

4. Scalability: Since WSN can be deployed with hundreds or thousands of sensor nodes; the scalability is one of the metrics that have to be considered. Network scalability, according to [64], is the capability to handle the high number of nodes during the initial network design phase. To measure network scalability, many studies vary the number of sensor nodes with other metrics such as energy consumed, delay, throughput, or network lifetime[62], [64], [65].
5. Throughput: In specific applications such as monitoring application, the number of data delivered to the destination is an important metric. It is evident that throughput is defined as the number of packets delivered per second or per round [46]–[48]. Other different terms of throughput such as the number of messages received and the number of the data signal received also applied in many works, such as in [32], [58].
6. Packet delivery ratio: Since a shared wireless communication is unreliable and asymmetric[62], some packets can collide in the network. Furthermore, an intermediate node can reject packets when its buffer is full. This colliding and lost packet increase as the number of packets in the network grows. Packet delivery ratio is a metric to compare the number of packets received successfully in the destination with the number of packets sent[32][46], [61]. Meanwhile, authors in [63] introduced packet loss percentage, which is the ratio of the number of data packets lost to the total number of data packets transmitted in the network until its lifetime end, as one of the parameters to study their proposed approach.

Instead of those metrics, there exist some performance parameters which are rarely used. Those parameters are CPU running time[54], fairness[66], bandwidth utilisation[66], and stability period. The last metric, as used in [60], is the time range from the start of network operation until when the first node destroys (FND) whereas the instability period (IPL) is the period from the FND until the last node destroys (LND).

2.2.5 Applications of WSN

WSN offers a broad range of application in our daily life nowadays. It has been implemented in many areas, including industrial until healthcare. WSN's realisations such as smart factories[67], monitoring industrial parameters[15], can support the development of industry 4.0. There are a lot of implementations of WSN to monitor environments, and some of them are volcanic eruption monitoring[68], tsunami detection[69], oceanographic tracking [70], habitat monitoring[71], air pollutant monitoring[72][73], forest fire monitoring[74][75], and precision agriculture[76]. Telemedicine monitoring[77] and asset tracking in healthcare[78] are two famous examples of WSN in the healthcare area.

In general, applications of WSN can be classified into two main categories: tracking and monitoring applications[5][36]. In tracking applications, sensor nodes send data to the destination when a phenomenon is detected or the occurrence of a specific event[12]. Due to this characteristic, it is also named as event detection applications. Only targeted nodes are responsible for transmitting data to the destination. The tracking system can be a single spatial as well as a multi-spatial phenomenon. FastTrack[79], for instance, is a face tracking framework using WSN. On the other hand, in monitoring applications, data are sent by all nodes periodically to the destination. The reporting period is application dependent[12]. By way of illustration, authors in [72] proposed an air pollutant monitoring system using WSN. It is also equipped with a data analysis system to understand the status of air pollutant in a rural area.

Another taxonomy of WSN application is introduced by authors in [80]. The taxonomy of WSN applications is split into two categories: Category 1 WSNs (C1WSNs) and Category 2 WSNs (C2WSNs). In C1WSN, the multi-hop radio connectivity is implemented among and between WSN, with dynamic routing and high-density network. The monitoring environment for forest fire detection is an example of this category. On the contrary, C2WSN applications apply static routing with a low or medium density network and mainly single hop. Applications in the health area such as in-hospital emergency care and telemedicine are included in C2WSN.

Classification of WSN application can be based on the time-related constraint, as mentioned by authors in [81]. All the time-related limitations are lifetime, scalability, maintainability, sampling rate, power supply, and accusation and dissemination parameters. There are three clusters in this classification: Long-Term Application (LTA), Medium-Term Application (MTA), and Short-Term Application (STA). Applications with LTA cluster has network lifetime higher than 25920 hour and minimum 400 sensor nodes. However, MTA and STA can accommodate 50-400 nodes and lower than 50 nodes, respectively. A lifetime of MTA is around 720-25920 hour while in STA, 720 hours is its maximum lifetime. In term of the sampling rate, STA and MTA have a high rate medium rate respectively. All of these clusters prove a maintainable system.

QoS requirements can vary from one application to others[82]. In environmental applications, the first requirement is scalability[83]. Agricultural fields, habitat monitoring and monitored fire, can reach several tens of hectares, so the number of sensor nodes installed varies from dozens to thousands. Secondly, energy efficiency to support network lifetime is a must in this application[84]. Sensor nodes are powered with limited batteries. Therefore, a wireless sensor network deployed for such as fire detection should deplete energy very efficiently. Furthermore, a sensor network will usually operate in harsh environments and therefore should be able to deal with and adapt to harsh conditions. It should be able to recover from node damages, link errors, high temperature, humidity, pressure, etc. It is important to detect some parameters as early as possible and to estimate the location with high accuracy in an environmental application such as forest fire. A forest fire usually grows exponentially, and it is crucial that the fire should be detected and interfered in about six minutes to prevent the fire from spreading to a large area.

Applications of WSN in healthcare have different characteristics. In healthcare monitoring activities, for instance, some delay is allowed. In contrast, the emergency healthcare application such as heart attacks or sudden falls in a few seconds or even minutes will suffice for saving lives considering that, without them, these conditions will not be identified at all. Therefore, the principal advantage of the healthcare system is to provide real-time identification and action taking in pervasive[85]. Furthermore, the physical design of sensor nodes should support mobility and portability because this device has to be worn by the patients all the time. The sensor devices must be designed with the aim of providing the highest degree of mobility for the patients, which requires the combination of several network technologies like RFID and Near Field Communication (NFC). Finally, due to the confidentiality of the physiological data security sent to the hospital, the security issues also need to be fulfilled in the healthcare system.

While energy efficiency is the most important in commercial sensor networks, network connectivity becomes more significant than energy problems in tactical military WSNs. There can be missed or delayed mission-critical information due to only a few isolated sensor nodes in the network, and this may result in a wrong decision on the battlefield. Also, this application must fulfil the Quality of services such as low delay and high reliability in case of the critical application.

2.3 Routing in WSN

As stated in section 2.2, the main task of sensor nodes is to deliver data to the BS efficiently. When a sensor node is far away from the BS, there should be an efficient method to route packets from the sensor node to the BS considering many factors, such as distance, energy, link reliability, and etch. In the networking area, this method is referred to as a routing technique. This section presents the classification of routing and factors influencing in designing effective routing.

2.3.1 Classification of Routing

Due to different ways to forward data from a source to a destination, routing protocols can be classified into diverse perspectives. The general taxonomy is firstly introduced by [39], in which the classification of routing protocols is based on network structure and protocol operation. According to the network structure of WSN, there are two types of routing, namely flat routing, and hierarchical or clustering routing[80][32]. In flat routing, every sensor node performs the same task, and the cooperation from all nodes are required to perform an effective routing. This type has some benefits, including supporting node mobility, a minimal number of overhead, and multiple routes for increasing the robustness[80][32]. Some well-known routings of flat routing are flooding, gossiping, Sensor Protocols for Information via Negotiation (SPIN), and Directed Diffusion. On the other hand, sensor nodes in clustering routing possess different functions depending on their levels. In this type of routing, sensor nodes are sorted into clusters regarding distance, and these nodes are called as cluster members (CM). CMs perform the first level. There is a cluster head (CH) organising CMs. A collection of CHs is in the second level, and mostly they are selected according to their energy and distance to the BS[27]. After receiving data from its members, CH forwards data to the sink or BS. Multi-level can be performed in this routing to enhance energy efficiency, routing scheme, stability, and scalability[86][87][39]. The effectiveness of clustering routing has been exemplified in a report by Heinzelman[27]..

Routing technique also can be divided by QoS requirements that want to be achieved. This lead to the second classification of routing, namely QoS-based routing. As stated in subsection 2.2.4, performance metrics such as energy efficiency, delay, throughput, scalability and etch are metric objectives of design development of routing protocol. Works in [27][29], [49], [50], [59], [88]–[90] are examples of energy efficient routing while authors in [55], [91]–[93] proposed routing for delay constraint.

The number of paths in establishing a route is the third classification of routing. Authors in [94] also classified routing with this method. The first class of this classification is termed single path routing, in which the communication between the node and the BS is performed by only one path. It is a simple protocol since the route can be created in a specific period. Furthermore, its scalability is high due to the algorithm is stable for a different number of nodes. The second class is multipath routing, which chooses multiple paths to send data from a node to the BS. This routing is more reliable, secure, and load balance than single path routing since there are many optional links in delivering data.

Authors in [33][95] consider the computational complexity in sorting routing protocol in WSN. They classified routing into two groups: classical and intelligence-based routing. Generally, classical or traditional routing adopts routing methods for Mobile Ad-hoc Network (MANET). The complexity of this routing is very low, and some of them are distributed routing which is no need overall network information. In contrast, intelligence-based routing applies computational intelligence approaches such as ant colony optimisation, fuzzy logic, neural network, reinforce learning, and genetic algorithm. Most of the intelligence-based routing need overall network information and have higher processing demands.

Depending on how the source chooses a route to the destination, routing is divided into three categories, namely proactive, reactive, and hybrid routing[32][39]. Proactive routing finds all routes before it needs to transfer data. It saves this information in the routing table and maintains it. When topology changes, this method should update the table. Since all routes are collected in the table, data can be sent directly without any delay because of finding routes. In contrast, reactive routing calculates a route on demand. There is no routing table and no updating processes. Unfortunately, it introduces an extra delay due to the route discovery process. The last category, hybrid routing, combines proactive and reactive routing.

2.3.2 Design Constraints

In designing effective routing, there exist some factors that have to be considered. These factors can be listed as follow:

1. Quality of Service (QoS): As stated in section 2.2.4, there are many performance metrics in WSN. As energy is the main constraint in WSN, many researchers have proposed efficient routings considering network lifetime. A cluster-based routing proposed by [27], for instance, is an effective approach to reduce energy consumed by aggregating data from its member to the cluster head. Many works have been developed with focusing on optimising the cluster head’s and cluster member’s selection. Another well-known routing approach aiming to enhance

network lifetime is multi-hop routing. Compare to direct transmission, multi-hop routing is more energy efficient for a long distance communication since the transmission power of a wireless radio is proportional to distance squared or even higher order[87]. Routing in WSN can lead to the variation of delay in many perspectives. Multi-hop routing can cause packets to pass through many intermediate nodes before they arrive in the destination. There are queening and processing delay in every node, and therefore, the additional delay will increase as the number of intermediate nodes grow. Shortest path routing can be an option to decrease delay. Unfortunately, when there are many packets with the same route, delay of these packets will increase, and indeed there exists an increasing number of lost packets. Also, the routing protocol can enhance network scalability by performing a hierarchical network. In this network, there are levelling network based on their functionalities. Nodes sensing the environment is in the low level while the intermediate level is nodes aggregating data from sensor nodes. The high-level network is nodes which are close to the BS. Works in [96]–[98] are some hierarchical routing.

2. Node deployment: Sensor nodes can be deployed randomly or pre-defined[33]. In rural application, commonly nodes are scattered randomly, and they have to organise their network independently. In this case, the route discovery phase is the initial step of the routing protocol. On the other hand, in pre-defined deployment, the position of nodes initially is set up by the user such as in building applications. As a result, no route discovery processes are needed in this mode.
3. Fault tolerance: There are possibilities that sensor nodes in the network are dead or fault because of power drained, physical damage, or any environmental causes such as earthquake or flood. In these cases, the robustness of routing should not affect network performance as a whole. In emergency applications such as forest fire monitoring, when a node as cluster head is burnt, data from this cluster will not arrive at the BS. As a consequence, a lot of vital information is loss and fire management system will make a wrong decision.

4. Mobility: Most studies on routing protocol is assumed that sensor nodes are fix or not mobile. Mobility of node can influence the routing stability as well as energy consumed in sensor nodes as a whole[33].
5. Application: WSN is application-specific in which a considerable number of WSN applications leads to different requirements[34]. Therefore, routing in WSN must adapt to QoS requirements in every application. A multimedia application is a well-known application requiring high bandwidth as well as low latency. Meanwhile, in emergency applications, metrics such as latency and robustness have to be accommodated in designing effective routing.
6. Data communication: There are three types of data communication in WSN, namely event-driven, periodic, and on-demand[61]. In the event-driven mode, data from a source to a destination is forwarded when an event in sensor nodes exists. Routing in this data mode has a lower delay and a good response. On the contrary, users request data from sensor nodes in the on-demand mode. Therefore, the BS initiates routing in the network. In the periodic mode, data sent periodically to the BS makes routing has to be performed at the beginning of time.

2.4 Medium Access Control (MAC) in WSN

There are many layers to perform communication in WSN; one of them is Medium Access Control (MAC). MAC is responsible for managing access to the shared medium. It controls when packets can be sent to the destination. Collisions among packet can be minimised by an effective MAC. Since a lot of proposed MACs for WSN have been designed by scholars, the classifications of MAC are needed to give an easiness in developing a valid MAC. This section starts by briefing classifications of MAC in WSN. Following this, some influential factors in creating MAC are presented.

2.4.1 Classification of MAC

Classifications of MAC have been presented in many kinds of literature, but in general, MAC is categorised into three classifications, namely contention free, contention based, and hybrid[12], [24], [99]–[101]. Contention-free is a method to access the shared medium by synchronising transmitting packets among sensor nodes, and therefore, there are no collisions in the network. In this approach, the sensor nodes can only transfer data in pre-defined slots, which can be assigned distributed or centralised. In the centralised methods, slots for all sensor nodes are determined by the BS, while in distributed ways, a sensor node called as a Cluster Head (CH) acts as the BS. A well-known contention free is Time Division Multiple Access (TDMA), and it has been implemented in WSN such as E-TDMA[58], SS-MAC[102], HEEMAC[52], and BMA-MAC[103]. E-TDMA is a pioneer of TDMA-MAC for clustering topology, and CHs, which are selected randomly using a threshold probability, assign TDMA frames for its member. Contention-free is suitable for high throughput applications, such as monitoring applications. Furthermore, it offers a high packet delivery ratio and scalability.

The second group is contention-based MAC, in which the shared medium is contended by sensor nodes when they have data to be sent. Central coordinators such as CHs are not needed, and the shared medium is distributed. Many researchers derived contention-based protocols from Carrier Sense Multiple Access (CSMA). In CSMA, a node has to sense the medium if it has data that will be sent. When the medium is busy due to other transmitting done by other nodes, the node waits for a particular time until the medium is clear. Following this, it sends its data to the destination. Throughput of CSMA decreases as traffic in the network enlarges because there will be many sensor nodes contend the medium, and as a result, some of them do not find available medium to transmit their data successfully. In addition, because the sensor nodes postpone transmitting their data, delay of packets grows significantly. Because of these characteristics, this MAC can be implemented for event-driven applications, such as fire detection. Regarding the mechanism of duty cycling, contention-based MAC, in detail, can be categorised into two classes: synchronous and asynchronous slotted. Duty cycling is a method to save energy by changing the active and sleep state of the sensor node. In synchronous slotted, the time when neighbouring nodes wake or sleep is the same. The implementations of synchronous slotted can be found in S-MAC[66] and D-MAC[104]. On the other hand, sleep or wake time for adjacent nodes are different in asynchronous, and this is a challenging task of this approach. Some examples of asynchronous slotted are B-MAC[105] and X-MAC[106].

Hybrid MAC is the third group of the classification, which is a combination of contention-free and contention-based MAC. A good illustration of this is the approach proposed by authors in Z-MAC[107], which is a combination of TDMA and CSMA.

2.4.2 Design Constraints

As routing, limitations in WSN bring some constraints in designing an effective MAC. These constraints can be explained as below:

1. Quality of Service (QoS): As stated in 1.2, MAC directly manages the transmitter and receiver of the communication module in WSN. Since these processes spend a lot of energy, the first constraint in designing an effective MAC is energy expenditure. There are four sources that caused energy drain in MAC: idle listening, data collision, overhearing, and control overhead[38]. S-MAC is an example of low energy MAC by reducing idle listening of sensor nodes. MAC layer has to take into account the average end-to-end delay. In contention-based MAC, delay goes up as the load in the network increases. This happens because many packets queue in the buffer for a long period before the medium is clear. To overcome this issue, SMED[108], which is MAC considering load in sensor nodes, was proposed. This MAC assumed that the nodes, which are close to the destination, have a higher capacity than others since they forward load from others. As a result, those nodes should wake longer than others to forward data with minimum delay. Moreover, this approach can improve network throughput, other's QoS metric and lost packets in the forwarder nodes are minimal. Network scalability can be improved by designing an effective MAC, and one of the methods is clustering or hierarchical MAC. Some of these MAC are E-TDMA[58], HEEMAC[52], and B-MAC[103].
2. Application: MAC protocols in WSN are application dependent[101]. A certain application has some requirements which bring some constraints in designing

MAC. For instance, multimedia applications need low delay and steady flow data[26], and therefore, multimedia MAC should accommodate these requirements. An excellent example of multimedia MAC is Diff-MAC[109], which applies a service differentiation mechanism for heterogonous traffic classes.

3. Traffic pattern: It is essential to study the characteristics of traffic delivered into the network in designing an effective MAC[101]. Traffic in WSN can be classified into three categories: local traffic, sensor-to-sink traffic, and sink-to-sensor traffic. Local traffic is traffic from sensor nodes to the cluster head. MAC in this traffic can accommodate aggregation to reduce energy spent. Sensor-to-sink traffic mostly happens when nodes deliver data directly to the destination or the BS. The last type is sink-to-sensor traffic, which is request traffic or control traffic. All sorts of traffic require different handling since they have different QoS requirements. Also, according to the time of occurrence, traffic can be event-driven, continuous, and hybrid traffic. The generation of event-driven traffic is influenced by detected events, which can be busty. In continuous traffic, packets always deliver to the destination periodically. The combination of this traffic, event-driven and continuous, is hybrid traffic. Hence, different mechanisms in MAC for heterogonous traffic achieve dynamic QoS.

2.5 Clustering Based Routing Protocol

As stated in 2.3.1, clustering routing is a promising approach to achieve energy efficiency due to aggregation. Generally, clustering routing can be grouped in term of the method to perform clusters, which can be done locally or not. If the clusters and the CHs are selected locally, every sensor node plays a role in selecting the clusters and the CHs, and this is called as a distribute routing. Some examples of this are LEACH[27], Multi-hop hierarchical[31], and PEAL[96]. Meanwhile, if the BS manages the formation of clusters and selects which sensor nodes become the CHs, it is named centralise routing. The BS receives information from all sensor nodes, then performs clusters and chooses the CHs in every cluster. Some works in [27], [51], [90], [110], and [111] are examples of centralise routing. The combination from both approaches is known as hybrid in which the establishment of the clusters and the CHs are done with different approach, locally or not, such as in [112] and [113].

Works in [114] classified clustering into two main classification: hierarchical and partitional. In the first classification, the formation of clusters can be done from top to down or vice versa. Here, there are many levels of clusters, and it is performed by iteratively. The opposite of the first classification, the second one, is a method to group sensor nodes into k-clusters without levelling, only one level in the network. To get an optimal cluster, this classification applied some optimisation parameters, including distance, remaining energy, density of sensor nodes, and data aggregation. LEACH, LEACH-C, and LEACH-ED[115] consider distance to group sensor nodes. HEEMAC[52] groups nodes according to remaining energy, while work in [116] combines nodes based on data aggregation in one cluster.

Clustering methods have developed fast, and authors in [114] briefed the variants of it into six variations. The first one is graph (theoretic) clustering, which is an approach that used a graph to present a cluster. Minimal spanning tree (MST) is a well-known example of this approach. Model based clustering, the second variation, finds the best clusters with some optimal mathematical models, and introduces a class or concept in every cluster. Two examples based on this variant are decision tree and neural network. Clustering approach assuming data as a mixture of several distribution and aiming to identify the distribution of clusters is known as mixture density-based clustering. Grid-based clustering, the next variant, performs a set of grid cells and assign members to those cells. Then, this approach calculates the density of each cell, and tries to distribute data uniformly. STING (statistical information grid approach) is one famous example of grid-based clustering. The newest clustering approach, evolutionary approaches-based clustering includes evolution strategies (ES), evolutionary programming (EP), genetic algorithm (GA), particle swarm optimisation (PSO), and colony optimisation (CO). Other variants based on optimisation are search based clustering, collaborative fuzzy clustering, and multi-objective clustering.

2.6 Energy Model in WSN

As stated in 2.2.4, the main issue in developing WSN technology is energy constraint. Therefore, all layers of WSN goals to enhance energy efficiency of sensor nodes. To analyse energy drained in a sensor node, an appropriate energy model is required. In this section, the energy model, which is employed in this thesis, is presented.

The energy model proposed by authors in [58] is the model used in this thesis. Moreover, this model has been used in many proposed approaches, both routing and MAC layers, such as works in [46], [90], [111], [112], and [116]. As presented in subsection 2.2.1, there are four modules in a sensor node, and all these modules contribute to energy consumption in the node. But, here, the model only accommodates two modules, and they are listed below[32]:

1. Detecting and Processing Module. This module models energy consumption caused by activities such as sensing, signal sampling, analogue to digital conversion, sensor control, and data processing. Sleep and awake procedure in the MAC layer also happen in this module. Energy consumed for all these processes is known as the electronic energy (E_{elect}), and it is set to be

$$E_{elect} = 50 \text{ nJ/bit}$$

2. Transceiver Module. The dominant energy consumption in WSN node occurs in the transceiver module. This module includes two sides: transmitter and receiver, which has different characteristics, as presented in Figure 2-6. In the transmitter side, energy consumed is influenced by the size of packets, k, and the distance from the transmitter and receiver, d. On the other hand, the size of packets is the only influenced parameter in the receiver side. In wireless communication, channel propagation effects the power received on the receiver side. Here, two-channel propagations are applied: the free space model and the multi-path fading model, both already defined in Network Simulator (NS). A certain cross-over

distance ($d_{cross\text{-}over}$) is used as a threshold between those propagations. The cross-over distance is formulated as:

$$d_{crossover} = \frac{4\pi\sqrt{Lh_r h_t}}{\lambda} \qquad 2\text{-}1$$

Where

L is the system loss factor,

h_r is the height of receiving antenna,

h_t is the height of transmitting antenna,

λ is the wavelength of the carrier signal.

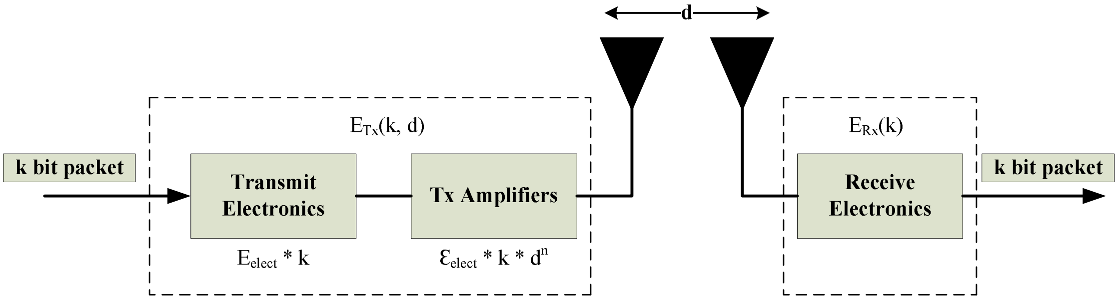

Figure 2-6. The energy model which is proposed by[58].

The power attenuation caused by signal propagation depends on distance. For short distance propagation or lower than $d_{cross\text{-}over}$, the propagation loss is proportional to d^2, while if the range is higher than $d_{cross\text{-}over}$ or long-distance propagation, the propagation loss is proportional to d^4. Hence, if a packet with k bit is sent to the destination, energy consumed in the transmitter side is:

$$E_{Tx} = k.E_{elect} + k.\varepsilon_{fs}.d^2 \qquad for\ 0 \le d \le d_{crossover} \qquad 2\text{-}2$$

$$E_{Tx} = k.E_{elect} + k.\varepsilon_{mp}.d^4 \qquad for\ d > d_{crossover} \tag{2-3}$$

The parameters ε_{fs} and ε_{mp} are the amplification factors for free-space propagation model and two-ray ground propagation model respectively.

On the other hand, energy consumption in the receiver side is only affected by packet size, which is formulated as:

$$E_{Rx} = k.E_{elect} \tag{2-4}$$

2.7 Summary

This chapter has presented details on Wireless Sensor Network, which consists of its elements, topologies, standard, quality of service, and applications. WSN has two main components: a sensor node and a base station. A method of how the sensor node and the base station connected is called network topology, and there are three standard topologies in WSN, namely clustering, mesh or flat, and mixed topology. Every sensor node communicates wirelessly using a standard. Here, there are four common standards presented in this chapter; ZigBee, WirelessHART, ISA100.11, and LoRaWAN. The performance of WSN is indicated by its Quality of Service (QoS) parameters. Every application of WSN has different QoS requirements. Furthermore, this chapter has explored routing and MAC protocol with their classifications and constraints. Since the main issue in WSN is energy constraint, this chapter also provides an energy model in general as well as the energy model implemented in this thesis.

Chapter 3: A Distributed Clustering Based on Node Health Status

3.1 Introduction

As was mentioned in the previous chapter, routing is one of the approaches to tackle WSN issues. Different types of routing encounter various problems that should be solved. Although the main problem in WSN is energy constraint, many studies have proposed new routing techniques considering other issues such as delay, fault tolerance, scalability, and throughput[39].

One of WSN applications bringing much impact on social and human life is emergency applications. Forest fire monitoring using WSN can be considered as an excellent example of emergency applications. In this application, sensor nodes can destroy because of energy drained, or they are completely burnt out as the spread of fire expands. The network should not fail in maintaining the communication link. Therefore, fault tolerance is an essential metric in such applications.

A well-known routing protocol that has several advantages is clustering routing. This type of routing is suitable for increasing network lifetime due to data aggregation in every cluster[18]. The clustering approach, combining with a multi-level hierarchy, can improve network scalability[52], [86], [112]. Low Energy Adaptive Clustering Hierarchy (LEACH) proposed by Heinzelman in [58] is an example of a distributive clustering routing enhancing network lifetime. Sensor nodes are grouped into clusters independently without controlling from the BS. A cluster head (CH) leads a cluster and manages wireless communication between them. A sensor node is selected as a cluster head if its random probability is lower than a certain threshold probability. Because of randomness in the LEACH algorithm, any nodes in the network can be elected as CHs and the total CH varies depending on both probabilities.

Figure 3-1 displays sensor nodes communication using a multi-hop clustering approach deploying in a specific emergency application, such as forest fire monitoring. There are three CHs and one BS. The first figure is the condition where no fire exists in the environment. All CH collect data from their CMs and send them to the BS via the intermediate CHs. On the other hand, the second figure illustrates the third cluster (CH3) detecting a fire which is close to it. Since CH3 is the closest CH to the BS, it acts as an intermediate node that forwards few data from this cluster and other CHs to the BS. As the fire spreads, CH3 is burnt out, and all data from this CH and other CHs will not reach the BS. These data are vital information since they contain messages regarding the location of the fire.

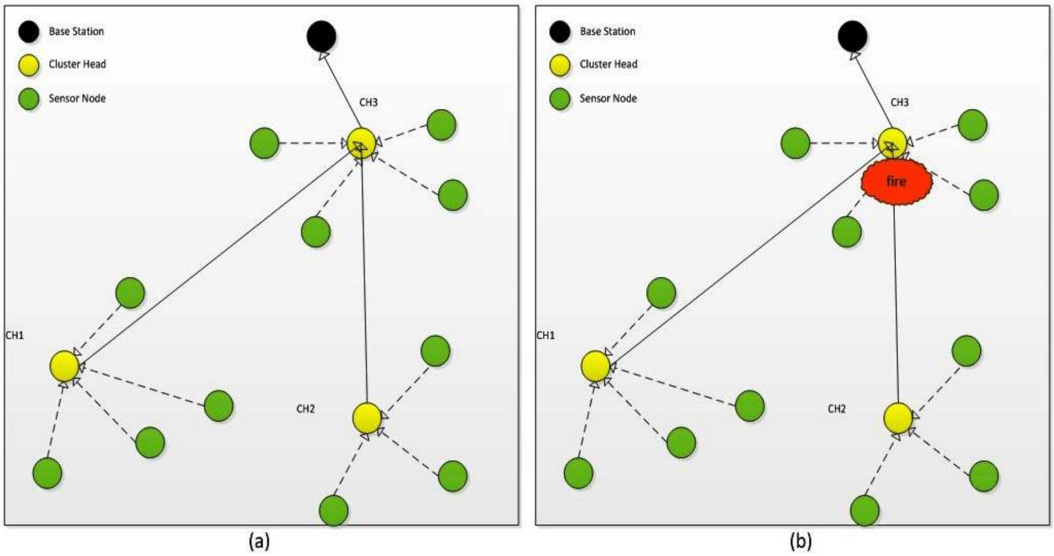

Figure 3-1. Two cases in choosing a CH for forest fire applications.

In order to circumvent many losses of data, a clustering approach that considers the health status of a node is proposed. This method avoids choosing a CH which is going to be burnt out in an unpredicted time. Furthermore, the approach classifies nodes in three different statuses, namely, safe, danger, and dead node. Only nodes in safe statuses can be elected as CHs. By doing this, the network throughput is stable. Moreover, multi-hop communication applied in this approach can prolong network lifetime as well as energy efficiency. This chapter explores the node failure caused by disaster events such as a fire in forest fire monitoring. Specifically, this chapter analyses the effect of choosing burnt nodes as CHs to the network performance, namely network lifetime and throughput.

This chapter is divided into five sections. Section 3.2 aims to provide insights into the range of researches about clustering routing with focussing on emergency applications. This is followed by section 3.3, which proposes the approach to enhance fault tolerance and throughput. Having introduced the proposed approach, scenarios and parameters used in the NS2 simulation are presented in section 3.4. This section also contains performance metrics and their formulations implemented in the simulation. Following this, section 3.4 exhibits simulation results and discussions comparing the proposed approach with LEACH and LEACH-C. This chapter ends with concluding findings in section 3.5.

3.2 Related Works

As was pointed out in the introduction of this chapter, a significant performance in emergency applications is fault tolerance. Some studies have revealed that considering this metric can also enhance others such as throughput, robustness, energy efficiency, and delay[117][118]. This section explores routing protocols that focus on fault tolerances especially in emergency applications. That is, some routings dealt with the node health status are discussed in this part.

LEACH [58] is a clustering routing which is suitable for monitoring applications such as forest fire or tsunami monitoring. The operation of LEACH is split into two phases: a set-up phase and a steady phase. In the set-up phase, every sensor generates a random probability and compares its probability with a threshold probability $P_i(t)$, which is formulated as:

$$P_i(t) = \begin{cases} \dfrac{k}{N - k * (r \, mod \, \frac{N}{k})} & , c_i(t) = 1 \\ 0 & , c_i(t) = 0 \end{cases} \qquad \text{3-1}$$

Where k is the expected total CHs, r is round, and N is total nodes in the network respectively. Hence, $C_i(t)$ is an indicator determining whether a node has been a CH in the most recent round or not. If a node has been a CH, $C_i(t)$ is zero and vice versa. Sensor nodes with lower random probabilities than $P_i(t)$ can be CHs for this round and send broadcast messages to others. In the steady phase, sensing data from sensor nodes are forwarded to the CH before they are sent to the BS. In the CH, those data are aggregated to minimise energy drained. LEACH assumes that sensor nodes always have data to be transmitted and it adopts Time Division Multiple Access (TDMA) in accessing the medium to prevent any data collision. As a result, this protocol has a higher throughput and network lifetime. Also, it is a distributive algorithm in which the routing protocol is initiated without controlling from the BS. Due to these characteristics, LEACH is a leading clustering routing, and there are several proposed algorithms developed based on it. Heinzelman also proposed a centralised clustering routing, which is named LEACH-Centralised (LEACH-C)[58]. In this routing, all nodes have to inform their position to the BS. Following this, the BS chooses the best CHs for every cluster using the simulated annealing algorithm. The elected CHs notify their members after receiving the information from the BS. Both LEACH and LEACH-C do not consider the node health statuses, which are the condition of nodes whether they destroy, burnt out or safe.

Authors in [119] proposed a reactive routing for cluster network called Threshold sensitive Energy Efficient sensor Network (TEEN). Like LEACH, there are two phases in this routing. Cluster formation is performed in the set-up phase and follows LEACH. On the other hand, in the steady phase, this protocol has a different approach in sending data to the CH. TEEN introduced two thresholds, namely, Hard Threshold (HT) and Soft Threshold (ST). The hard and Soft threshold is a threshold value of the sensed attribute of the sensor node. If the sensed attribute reaches HT for the first time, it will be sent to the CH. Furthermore, the attribute from the node will remain in the node's memories unless the difference between the current and previous value is higher than ST. As a result, there is only a small number of data that are sent to the BS and this feature is not suitable for monitoring emergency applications.

To overcome the limitation of TEEN, Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network (APTEEN) is proposed[113]. APTEEN is a combination of reactive and proactive routing. To accommodate the hybrid functionality, it applies not only HT and ST but also new variables, namely schedule and counts time (Tc). The schedule is used to assign a slot for every node while Tc is a time range between two successive reports sent by a node. Unlike TEEN, cluster formation is done by the BS using simulated annealing, the same approach as in LEACH-C. The BS can request data by sending a query to a particular node. The node receiving this query replies by transmitting the query as well as data. Data from the node and a paired node which is closest to it are forwarded to the CH to perform aggregation. If there are no queries in the network, it uses TEEN. The number of data received in the BS using APTEEN is higher than TEEN. Unfortunately, there are a lot of complexities in APTEEN due to additional thresholds and the count time.

Environmental Monitoring Aware (EMA) routing introduces the node health status as one of the parameters to choose a neighbour's node to forward data[120]. The scale status is from 0 to 100 with 100 the best health. Other parameters used to select the best neighbour are the hop count and the Received Signal Strength Indicator (RSSI). The complete formula is:

$$M = \frac{health}{100} * e^{-hopcount} * e^{\frac{RSSI}{50}} \qquad 3\text{-}2$$

As was revealed in that equation, a node with the worst health status has the smallest opportunity to become the best neighbour. Because of this, EMA reduces link breaks, and as a result, network lifetime of EMA increases. After choosing the best route to the BS, a source node sends data with multi-hop communication until it reaches the BS. This routing uses the flooding technique to find a path from a source to the BS. The BS initiates a routeing process by broadcasting a routing packet to the network. Nodes receiving the packet forward it to the neighbour until it reaches the destination. If there are hundreds or thousand nodes deployed in the network, routing packets will increase. Additionally, this protocol applies the flat routing protocol without aggregation such as the clustering protocol. Consequently, a monitoring application is not an area of implementation of this routing.

A routing protocol utilising the energy of nodes which are going to destroy is proposed by A. Jamil, et., al in [121], namely Maximise Unsafe Path routing (MUP). This approach aims to enhance network lifetime by optimising energy usage of nodes that are about to fail. It also introduces the node health status as a parameter in selecting the forwarder node, which is classified as:

1. SAFE: Initial stage and while there is no fire
2. LOWSAFE: One-hop away from a detected fire
3. UNSAFE: Fire discovered.
4. ALMOST-FAILED: Just about to be destroyed.

Moreover, other routing criteria, Expected Transmission Count (ETX), is used to count the total cost of each route in the network. ETX is a metric indicating the link's quality between two nodes. Hence, in the normal situation, packets from a source node will be sent to the intermediate node with the best link's quality. Meanwhile, if a particular intermediate node detects a fire, which is known as an UNSAFE node, the source node will forward packets to the UNSAFE node to utilise its energy. MUP is energy efficient routing, but since it is a flat routing, MUP is not appropriate for monitoring applications.

To minimise the number of transmissions from a sensor node detecting fire to the BS, authors in [122] introduced EFMP (Energy-efficient Fire Monitoring Protocol) for forest fire monitoring. It reorganises routes depending on fire propagation in the network. EFMP is a cluster-based routing, and the cluster formation is done by using cluster routing such as LEACH. This routing classifies CHs into two classes, namely master CH and slave CH. A CH can be a master CH if it is:

1. The first CH detecting fire.
2. The CH with the lowest number of transmission to the BS.
3. The CH with the closest distance to the BS.
4. The CH with the least number of sensors detecting fire.

5. The CH with the highest remaining energy.

The master CH is responsible for forwarding data from slave CHs to the BS after it informs slave CHs. Thereby, the energy spent by EFMP is less than others such as LEACH and TEEN. However, due to the complexity of this approach, the number of overhead packets is high.

3.3 The Proposed Approach

Having explored some studies that pertain to the routing approach for emergency applications, this section describes the approach that is used to study the effect of choosing danger nodes as CHs in the network performance of WSN. Moreover, the approach also introduces the priority method, which is assigned to packets sent by danger nodes.

Before describing the detailed approach, it is essential to define the node health status introduced in the approach. The node health status refers to the condition of nodes in sensing the environment such as fire. In this work, this status can be classified into three categories as listed below:

1. Safe: Sensor node which is far from the fire.
2. Danger: Sensor node which is close to the fire.
3. Dead: Dead node because it runs out its energy or is burnt out.

As in LEACH, the approach organises the process into two phases, namely, a cluster formation phase and a data delivery phase.

3.3.1 Cluster Formation Phase

This phase aims to arrange sensor nodes into clusters and to choose CHs in every cluster. Basically, it follows the LEACH algorithm by introducing the node health status as a parameter to select the CH as well as multi-hop transmission.

Figure 3-2 illustrates the complete process of the cluster formation phase. At the beginning of the phase, every node checks its current health status, and if its status is safe, it generates its random probability. Otherwise, if the node is in danger status, it does not have an opportunity to become a CH and sets itself up as a CM. After generating its probability, this node calculates the threshold probability $P_i(t)$ using equation 3-1. To be selected as a CH, the random probability should be lower than the threshold probability. When the node is chosen as a CH, it has to inform other nodes by broadcasting the advertisement message with the format as illustrated in Figure 3-3. The message consists of a message type, a node's ID, the position of the node in x and y coordinate, and a zone's code. The kind of message is ADV_CH, and the node's ID is a unique number of the node. The last part of the message is a unique number for every cluster. Following this, both the CH and CM wait for ADV_CH.

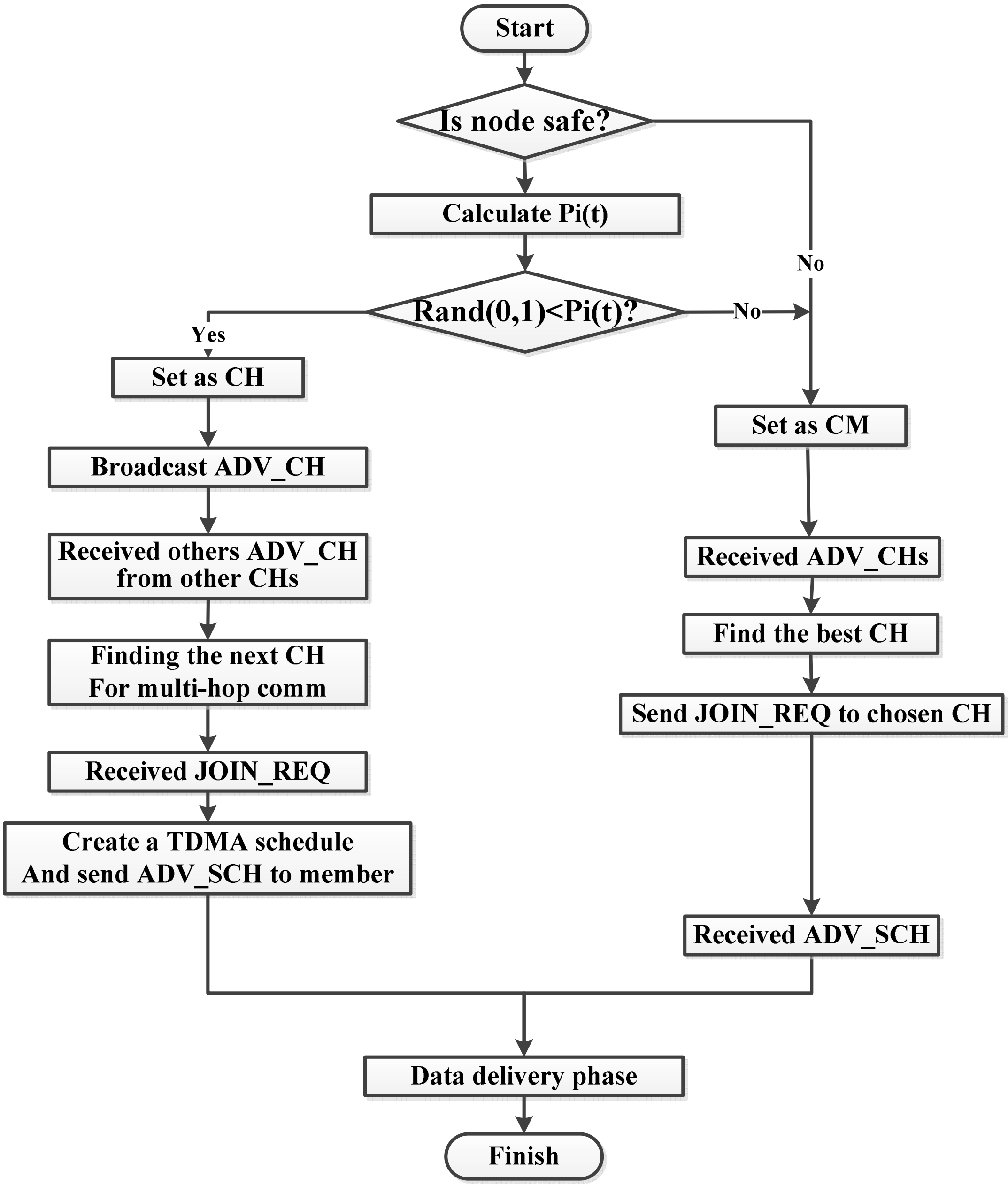

Figure 3-2. The flowchart of the cluster formation phase from the proposed approach.

Message Type	Node's ID	Node's Position	Zone's Code

Figure 3-3. The format of the advertisement message.

Message Type	Node’s ID	Node’s Status	Zone’s Code

Figure 3-4. The format of the join request message.

After receiving ADV_CH, the node finds the best CH according to the Euclidean distance from the node to the CH, and the closest CH will be elected as its CH. The position of the CH is obtained from the ADV_CH message. Every CM sends a JOIN_REQ message to the CH in a random interval. The structure of the JOIN_REQ message is provided in Figure 3-4. A node’s status refers to the node condition as explained above. If the node is in danger status, it has a higher priority than other nodes and has to send the JOIN_REQ message as soon as possible. Conversely, the CH which has received other ADV_CH messages determines the next hop CH if its distance is far away from the BS. Before sending data, every CH sets up a Time Division Multiple Access (TDMA) schedule and broadcasts this information as ADV_SCH to its member. Figure 3-5 shows the format of an ADV_SCH message. A TDMA schedule consists of the sequence of sending data for every CM in the same cluster. This formation phase ends after all CMs receive the ADV_SCH message from their CHs.

Message Type	List of CM	Node’s Position	Zone’s Code

Figure 3-5. The format of the TDMA schedule message.

3.3.2 Data Delivery Phase

There are two transmissions in the data delivery phase, namely intra-communication and inter-communication. Intra-communication is a transmission of data from a CM to the corresponding CH while the inter-communication relates to the delivery of data from a CH to the BS. Figure 3-6 displays these two communication processes. Communication from four CMs to CM5 is called as intra-communication while from CM5 to the BS is referred to inter-communication.

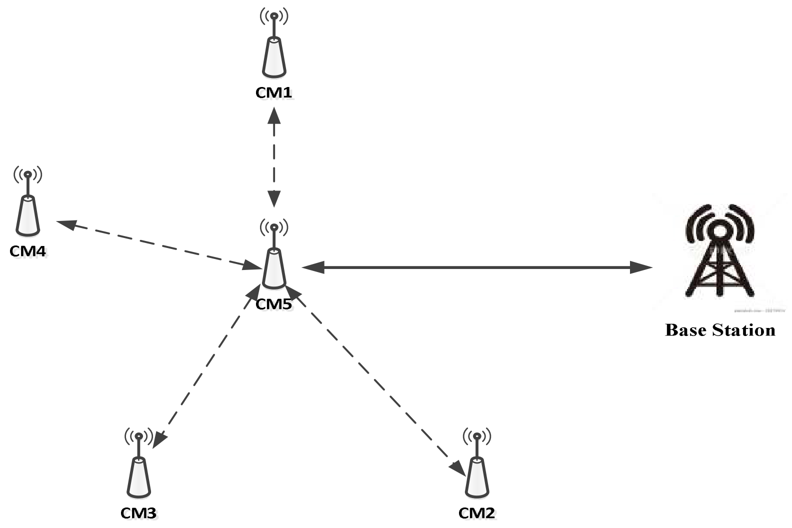

Figure 3-6. Intra and intercommunication in the data delivery phase.

The data delivery phase begins when CMs in the same cluster alternately send data to the CH according to the TDMA schedule. This TDMA approach is similar to LEACH, and it prevents collisions among packet data in the same cluster. Furthermore, the method is suitable as it is assumed that every CM, which is sensing the environment continuously, always has data to be delivered to the BS. An example of a TDMA frame with equal five-time slots is displayed in Figure 3-7. This frame also indicates that there are five nodes in the cluster. A node with the highest priority will be placed in the first slot.

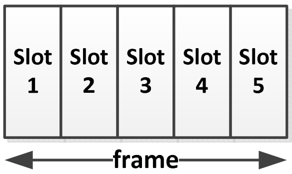

Figure 3-7. A TDMA frame with five slots.

To prevent interference among clusters, packet transmissions from CMs to CHs utilise the Direct-Sequence Spread-Spectrum (DS-SS) technique. This approach allows sensor nodes to send data at the same time using the same bandwidth. A unique code is assigned in every cluster to spread data before they are sent to the destination. This code refers to the zone's code as in the cluster formation phase. The first CH announcing itself to the network has the first code, the second CH advertising to the network has the second code, etc. Hence, combining DS-SS and TDMA can reduce interference.

After receiving all data from its member, the CH performs aggregation with the scheme as in LEACH. This scheme aggregates data fully with a ratio L:1, which mean that in every L bits of data which are sent to the CH, there is only one bit which will be forwarded to the BS. Following this, the CH forwards these data to the nearest CH which is in the direction of the BS or sends data directly to the BS if the BS is near to the CH. Here, the Carrier Sense Multiple Access (CSMA) approach is utilised in the inter-communication with a fixed spreading or zone's code.

3.4 Performance Evaluation

To analyse the effect of choosing a danger node as a CH, Network Simulator 2 (NS2) is used in this work. NS2 is a discrete event simulator that has been used to simulate communication networks such as wired as well as wireless networks[123]. Since the LEACH model is not supported by default NS2, a LEACH extension from MIT is patched into NS2[124]. The proposed approach is compared with LEACH and LEACH-C. Before running the simulation, it is necessary to discuss parameters, scenarios, and performance metrics which are used in this simulation as explained in the following subsection.

3.4.1 Parameters of Simulation

There are two groups of parameters, namely, radio and network parameters. Radio parameters are related to parameters of radio communication devices between a transmitter and receiver. On the other hand, network parameters are values needed when designing a WSN.

As discussed in chapter 2, LEACH energy is the power consumption model utilised in this simulation. The model utilises the propagation model as free space propagation or multi-path propagation depending on the distance between a transmitter and receiver. If the distance is higher than $d_{cross\text{-}over}$, multi-path propagation is exploited with energy consumption of 0.0013 pJ/bit/m^4. On the contrary, free space propagation, which is around ten pJ/bit/m^2, is used when the distance is equal or low than $d_{cross\text{-}over}$. On both sides, the electronic processing drains 50 nano Joule per bit of energy. It is assumed that the antenna height is 1.5 meter with 914 MHz frequency and 1 Mbps bandwidth respectively. All nodes are powered with the same initial energy of 2 Joules. The detail of radio parameters is shown in Table 3-1.

With regard to network parameters, this simulation is run with a hundred nodes. These nodes are deployed randomly with uniform distribution since this distribution is a reasonable approximation for emergency applications[125]. The area of the simulation is 100x100 meter square, and the BS location is in the outer space of the simulation, as illustrated in Figure 3-8. The simulation time is 800 seconds with ten repetitions. In addition, a data packet has 500 bytes long as in LEACH. The detail of network parameters is set out in

Table 3-2.

Table 3-1. The radio parameters in the simulation.

Parameters	Values
Radio energy for electronic processing (E_{elect})	50 nJ/bit
Radio energy for free space propagation (ε_{fs})	10 pJ/bit/m2
Radio energy for multi-path propagation (ε_{mp})	0,0013 pJ/bit/m4
System loss (L)	1
Antenna height in transmitter and receiver (h_t, h_r)	1,5m
The cross-over distance ($d_{crossover}$)	86,3m
Bandwidth (B)	1 Mbps
Radio frequency (f)	914 MHz

Wavelength of signal (λ)	0,328m
Initial Energy (Joule)	2

Table 3-2. The network parameters in the simulation.

Parameters	**Values**
Network area	100 x 100 m^2
Location of BS	50, 175
Number of Nodes	100
Simulation Time	800 second
Size of packet	500 bytes
Interface queue type	Drop Tail/PriQueue
Queue length	100

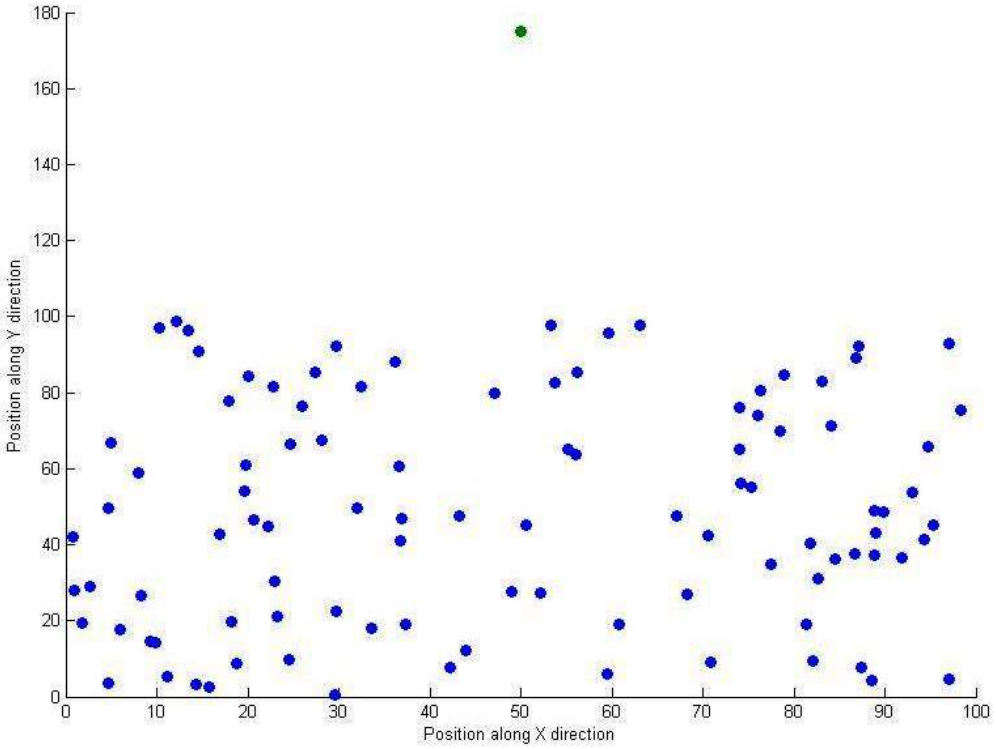

Figure 3-8. The sensor node distribution in the network area of simulation.

3.4.2 Scenarios of Simulation

To analyse the performance of the proposed approach correctly, the scenario of the simulation is set up in several situations. Firstly, the simulation is run with no burnt node and ten different topologies. Secondly, the number of danger nodes is varied from one to five nodes. These danger nodes are set up to be danger in the round where there are no dead nodes because of energy drain to avoid choosing nodes in danger which are going to get destroyed. Hence, danger nodes are established in the second round, and they are burnt out randomly in the next round. In LEACH and LEACH-C, the performance metrics are only calculated from these burnt out nodes becoming CHs. For instance, if there are three burnt out nodes in the network, it means that these nodes are all CHs.

3.4.3 Performance Metrics

The following metrics are applied in measuring the performance characteristic of the proposed approach.

- **Data received**: It is defined as the number of packets received in the BS over the simulation time.
- **Alive nodes**: This metric demonstrates how many nodes that are not dead due to energy drained or burnt off fire over the simulation time.
- **Energy consumed**: It is related to the total energy spent by nodes over the simulation time.
- **First Node Destroy (FND)**: It is the period from the simulation is started until the death of the first node because of energy drained.
- **Half Node Destroy (HND)**: It is the period from the simulation is started until half of the total nodes is dead owing to energy drain.
- **Average end to end delay**: It is the duration between the time at which the source node was originated and the time at which it reaches the destination node. Loss of packets in the network is not considered.
- **Packet delivery ratio**: It is defined as a fraction of total packets received by the BS to those sent by sources.

3.5 Simulation Results and Discussion

In this section, some simulation results indicating the effect of choosing burnt nodes as CHs are presented. The proposed approach is compared to LEACH and LEACH-C in connections with data received, energy consumed, packet delivery ratio, energy efficiency, FND, and HND.

3.5.1 Data Received

Figure 3-9 displays the number of data received in the BS over the simulation time when there are no burnt nodes in the network. It is clear that for all methods, there is a slow increase in the total packets collected in the BS as the simulation time raises. In the proposed approach, after 800 seconds, the BS gets around 48.700 packets. Meanwhile, at the end of the simulation, LEACH and LEACH-C receive about 40.400 and 59.400 packets respectively in the BS. Since LEACH-C applies simulated annealing in the clustering formation, clusters in LEACH-C are distributed uniformly. CMs in this approach sent packets with the highest rate, and as a consequence, the BS receives the highest data packets.

The total data obtained in the BS over the simulation time for three burnt nodes is illustrated in Figure 3-10. Graphs in this figure experience the same patterns as those in Figure 3-9. There is a slight decrease in total packets received at the end of the simulation owing to three burnt nodes in the third round. LEACH-C has the highest packets with around 57.000 packets, followed by the proposed approach with 47.200 packets. LEACH gets 38.000 packets, which is the lowest packets received. In these two cases, the percentages of packets dropped for the proposed approach, LEACH, and LEACH-C, are 3%, 6%, and 4% respectively. In short, packets lost in the proposed method are the lowest because there are no burnt CHs in the network.

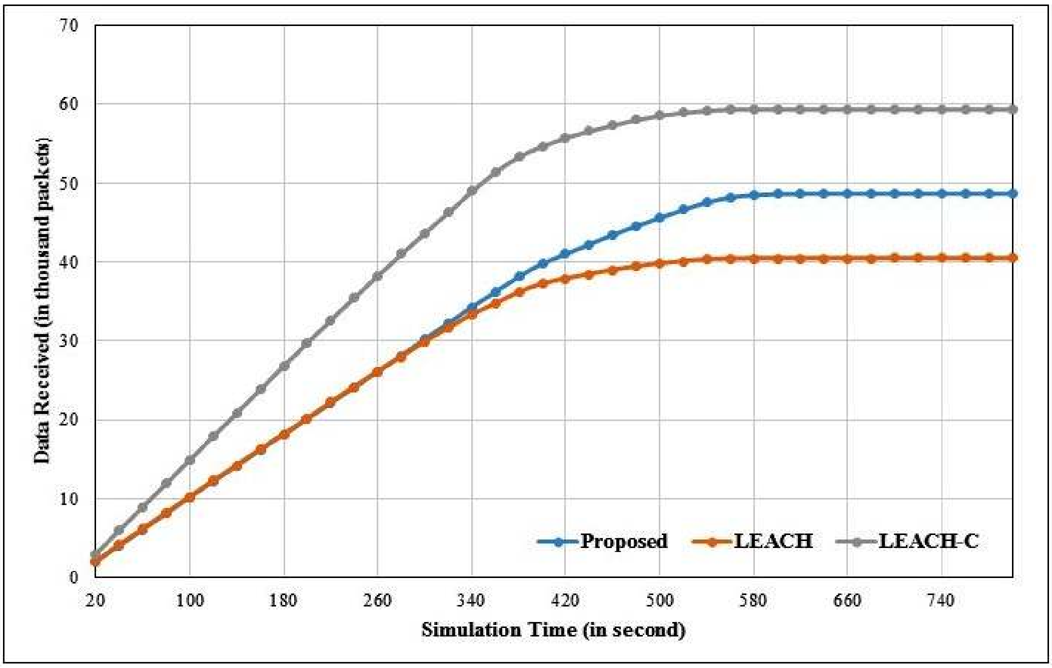

Figure 3-9. Total received data with no burnt nodes vs the simulation time.

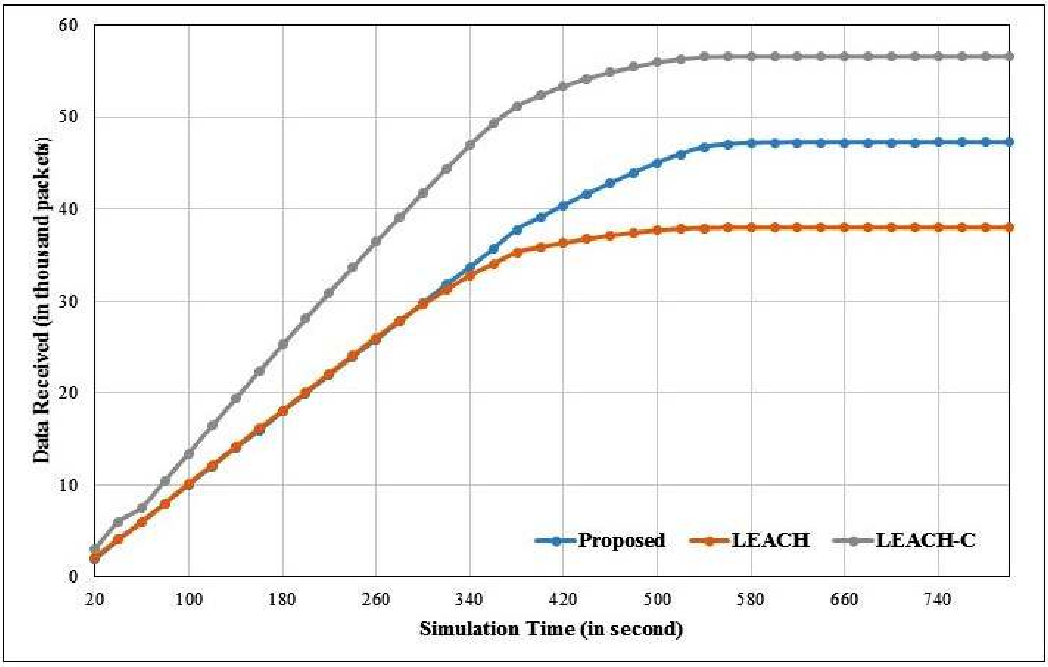

Figure 3-10. Total received data with three burnt nodes vs the simulation time.

Figure 3-11 plots the number of data received in the BS on different numbers of burnt nodes. Here, data collected in the BS is only calculated from the second to the third round or from 40 seconds to 60 seconds of the simulation time. Packets received in the BS using the proposed approach remain stable as the number of burnt nodes increases from zero to five. In LEACH, there is a slow fall in the number of data received. In contrast, LEACH-C experiences a sharp drop. When there is no fire in the network, LEACH and the proposed approach accept around two thousand packets in the BS, while LEACH-C has around three thousand packets. These three methods almost get the same total packets in the BS when two nodes are burnt out in the third round. Packets which are accepted in the BS go down significantly for LEACH-C with 662 packets on five burnt nodes. Nevertheless, in LEACH, the total packets decrease slowly with around 1600 packets. Since LEACH-C has a constant total CH, five burnt nodes mean that all CHs are burnt out in the network. As a result, packets collected in the BS are only those before CHs are burnt out. Conversely, LEACH has variable total CHs. If there are five burnt CHs, the minimal number of CHs, in this case, is five; therefore, the BS in LEACH receives more packet than in LEACH-C when five CHs are burnt out since some CHs are still alive and can transmit packets to the BS. The total burnt node does not influence the number of packets received for the proposed methods since the approach refrains from selecting danger nodes as CHs although their probabilities are lower than the threshold probability. As a result, data packets are constant for different numbers of burnt nodes.

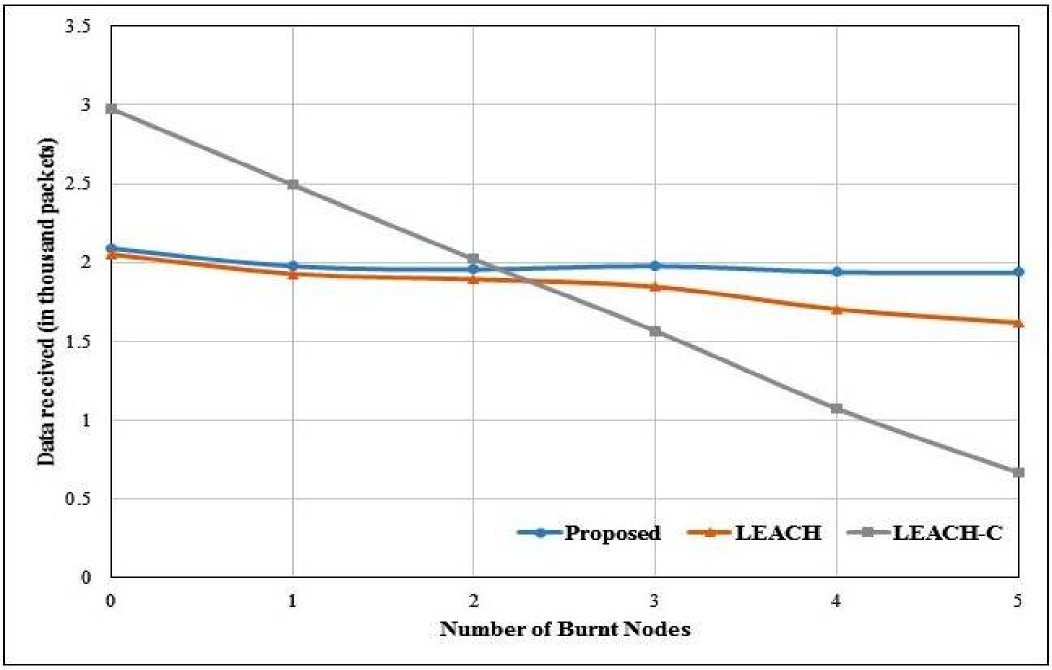

Figure 3-11. Total data received vs numbers of burnt nodes.

3.5.2 Energy Consumed

Figure 3-12 and Figure 3-13 plot the total energy consumed over the simulation time when there are no burnt nodes and three burnt nodes in the network. Generally, both figures experience the same pattern, in which there is a gradual rise in total energy spent as the simulation time grows. Total energy spent in Figure 3-12 is higher than in Figure 3-13 since there is the energy of three burnt nodes that do not contribute to the total energy of the network. These three nodes are burnt out when their energy is around 1.8 Joule. The rate of energy expenditure in the proposed approach is the lowest compared to others, and it remains stable after around 600 seconds for no burnt node and 580 seconds for three burnt nodes. In LEACH and LEACH-C, their total energy remains stable after 560 seconds when no fire is in the network. When three nodes are burnt out, the energy consumed rises slowly until 540 seconds for both LEACH and LEACH-C.

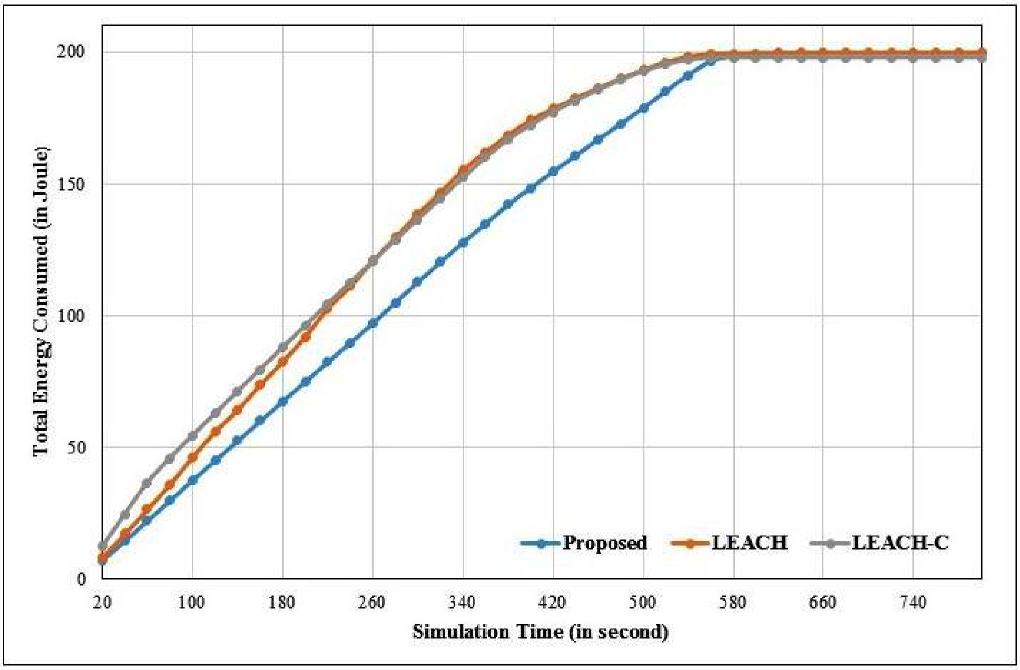

Figure 3-12. Total energy consumed when no burnt nodes vs the simulation time.

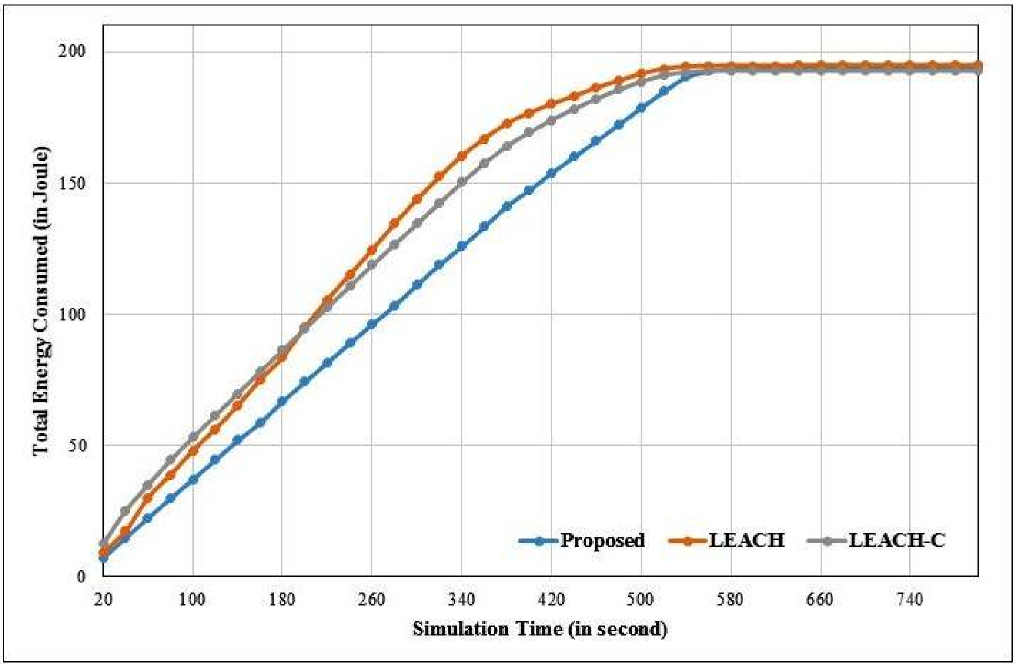

Figure 3-13. Total energy consumed when three burnt nodes vs the simulation time.

Figure 3-14 displays the impact of choosing burnt CHs to the total energy consumed of the network. This energy is the total energy spent of all nodes between the second and the third round, where some nodes are burnt out. In the proposed approach, there is no effect on energy consumed as the number of burnt nodes rises. Specifically, the energy remains constant at around 7.35 Joule. Meanwhile, this effect has a different pattern in LEACH and LEACH-C. As the total burnt CHs grow, the total CHs in LEACH increase. This brings the total power of all nodes goes up slowly. A high number of CH causes the total CM for every cluster is small. As a result, every CM transmit more data and consume more energy. Energy expenditure begins at around 9.1 Joule and ends at around 13.4 Joule. However, when there is no fire in the network, the total power spent by all nodes using LEACH-C is around 12 Joule, and this value goes down gradually until 7.7 Joule when five CHs are burnt out. This result may be explained by the fact that the reduction of energy consumed is caused by burnt CHs, in which they cannot send packets.

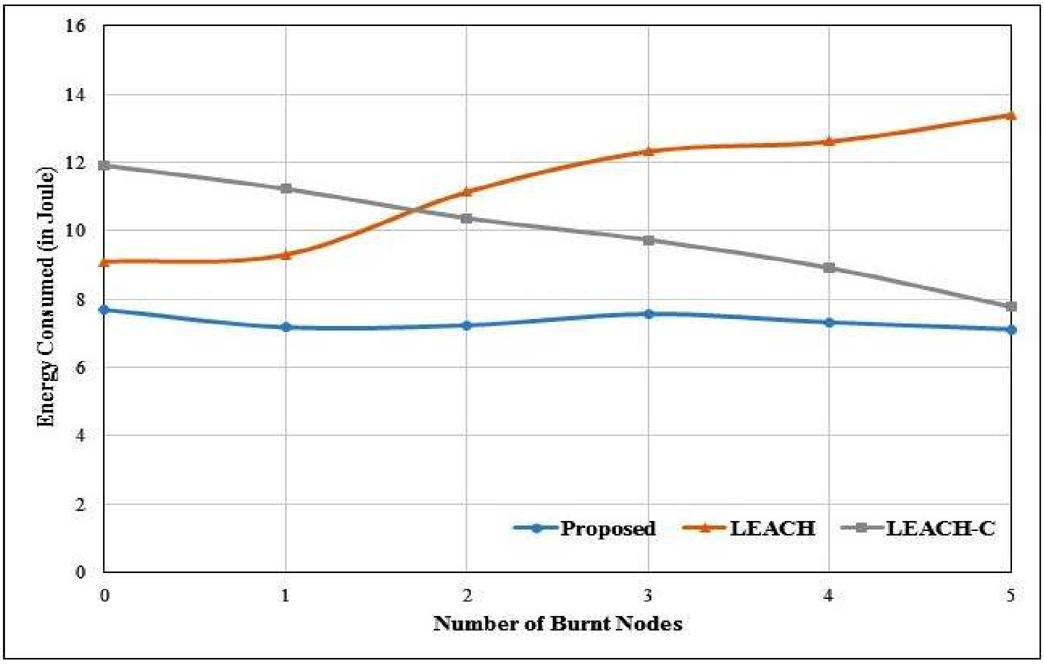

Figure 3-14. Energy consumed vs different numbers of burnt nodes.

3.5.3 Packet Delivery Ratio (PDR)

The ratio of data received to data sent on different burnt nodes is displayed in Figure 3-15. It is apparent from the figure that the packet delivery proportion of the proposed algorithm is stable even though the total burnt nodes raise from zero to five nodes. It seems possible that the result is due to the constant number of data accepted in the BS. Whereas, there is a gradual drop in the packet delivery ratio for both LEACH and LEACH-C. When there is no fire in the network, the proposed approach gets around 0.87 PDR, while LEACH and LEACH-C obtain around 0.84 PDR and 0.82 PDR respectively. On account of multi-hop communication in the proposed approach, the PDR of the proposed approach is the highest of the three. When the number of burnt nodes raises from one to five, this ratio remains stable. On the contrary, the PDR of LEACH and LEACH-C goes down to 0.82 and 0.80 when there are five burnt nodes. On average, there is 0.4 PDR drop in every one burnt node. Hence, selecting a CH which is going to destroy will drop the ratio of packet delivery around 0.4.

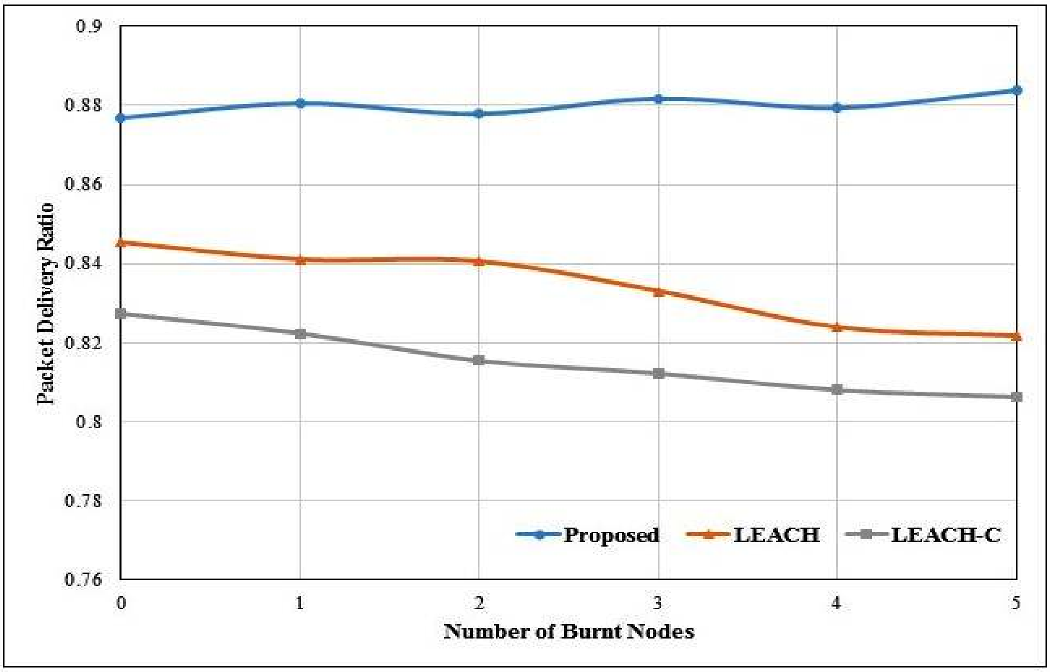

Figure 3-15. Packet delivery ratio vs different numbers of burnt nodes.

3.5.4 Energy Efficiency

The ratio between the total data received to the total energy consumed for different numbers of burnt nodes is provided in Figure 3-16. Generally, there is no different energy efficiency in the proposed method although the burnt nodes vary from zero to five. Again, it shows that selecting safe nodes as CHs results in the stability of the total data collected in the BS. As a consequence, energy efficiency is also constant. Otherwise, data packets received in the BS for LEACH and LEACH-C are gradually dropped since CHs in these approaches are burnt out before CMs finish sending their all data. Therefore, the ratio of data received to energy consumed is low as the number of burnt nodes gets bigger.

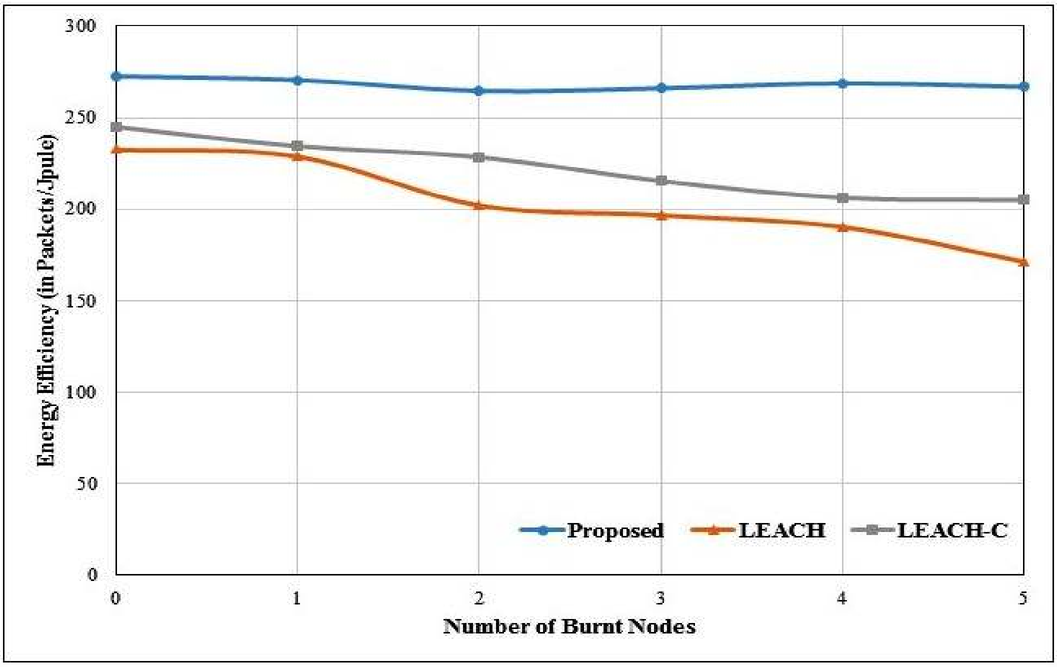

Figure 3-16. Energy efficiency vs different numbers of burnt nodes.

3.5.5 Total Alive Nodes

Figure 3-17 and

Figure 3-18 provide the number of alive nodes over the simulation time when there are no burnt nodes and three burnt nodes in the network. As can be seen from both figures, there is a slow reduction in the total alive node as the simulation time increases. Furthermore, they have the same pattern and start at a hundred nodes since the total nodes is a hundred. The proposed method outperforms others in these two cases due to multi-hop communication.

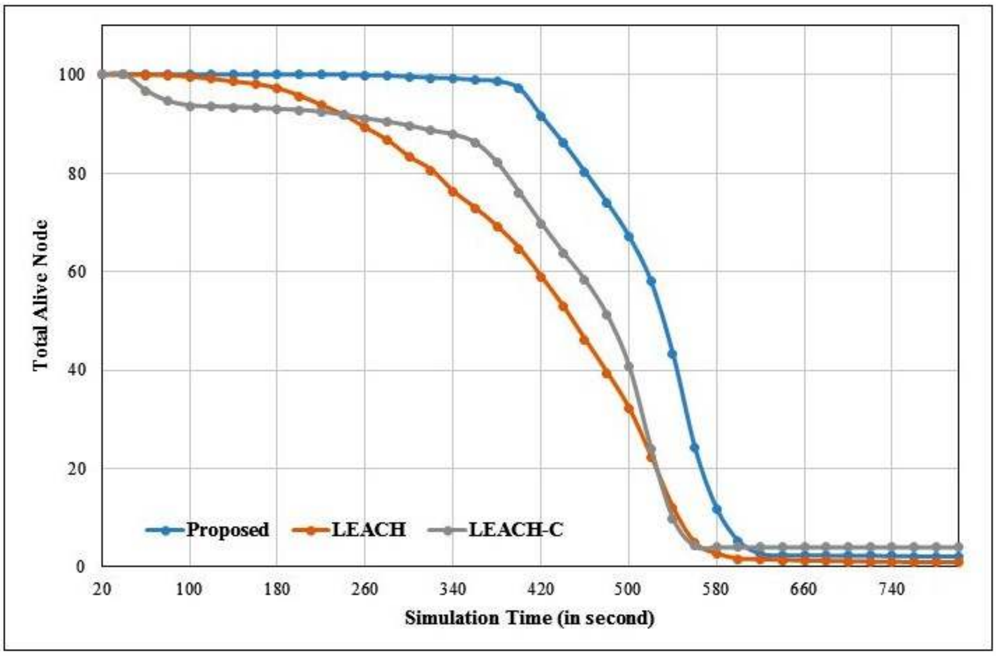

Figure 3-17. Total alive nodes when no burnt node vs the simulation time.

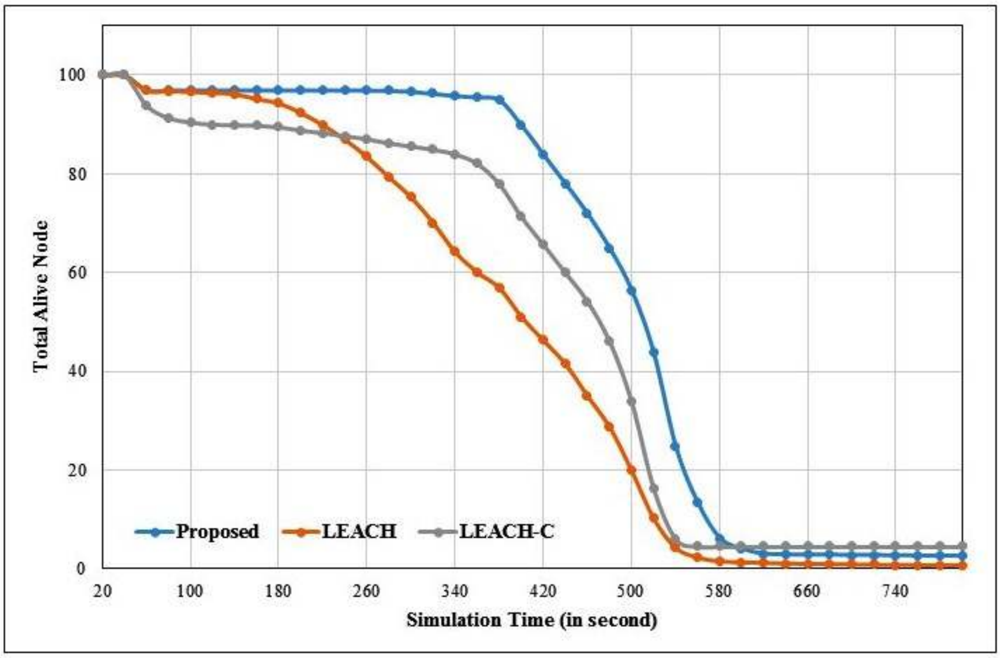

Figure 3-18. Total alive node when three burnt nodes vs the simulation time.

3.5.6 First Node Destroy and Half Node Destroy

Figure 3-19 is a bar chart comparing FND and HND for three approaches: the proposed approach, LEACH, and LEACH-C. In this case, there is no fire in the network. Generally, the proposed method gains the best performance in respects of FND and HND due to multi-hop communication. The proposed approach gains 380s in FND, which is around 31% better than LEACH and 47% better than LEACH-C. Furthermore, regarding HND, the proposed approach outperforms LEACH by 25% and LEACH-C by 15%.

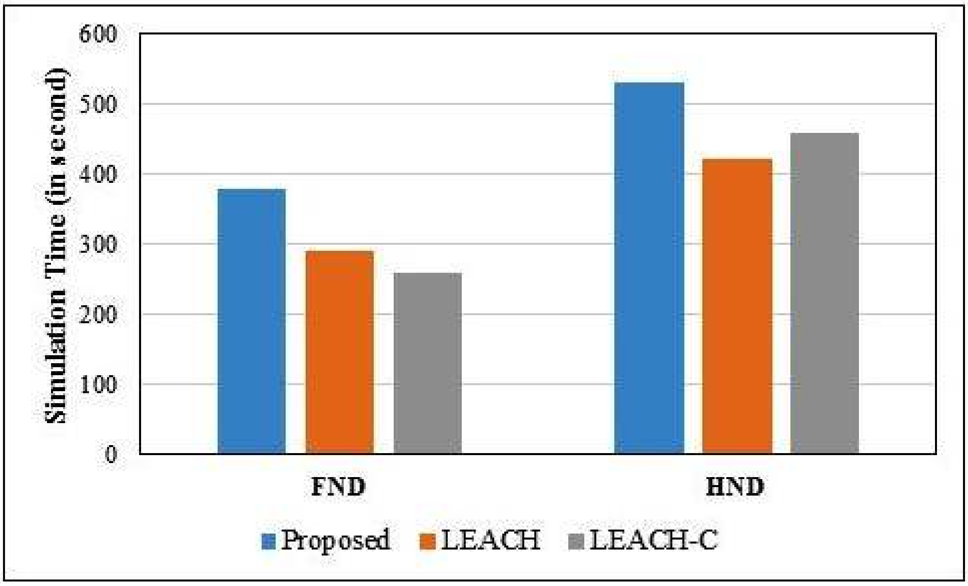

Figure 3-19. FND and HND when no burnt nodes.

Figure 3-20 demonstrates the effect of total burnt nodes on FND for the proposed approach, LEACH, and LEACH-C. In the proposed approach and LEACH-C, the time when the first node is dead remains stable for different numbers of burnt nodes. Meanwhile, there is a slight decrease in the FND of LEACH when the total burnt nodes are four and five. As explained above, the minimal total CHs in the network is the total of burnt nodes due to the random probability applied in LEACH. For instance, if there are five burnt nodes, the total CHs can be five, six, seven, or any number. As a result, LEACH dissipates more energy in this situation than others such as the proposed approach and LEACH-C.

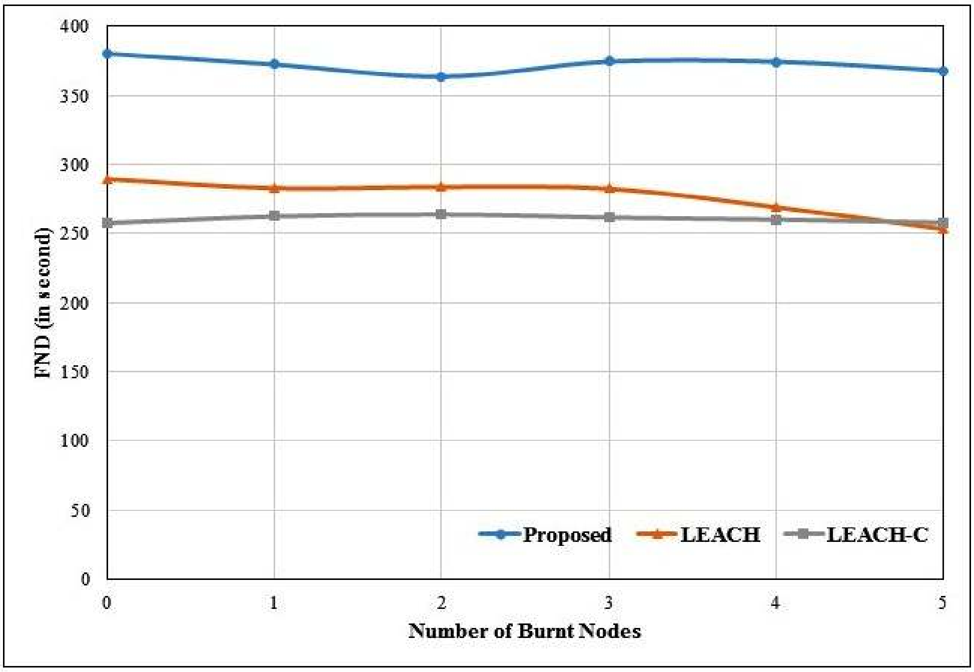

Figure 3-20. FND for different numbers of burnt nodes.

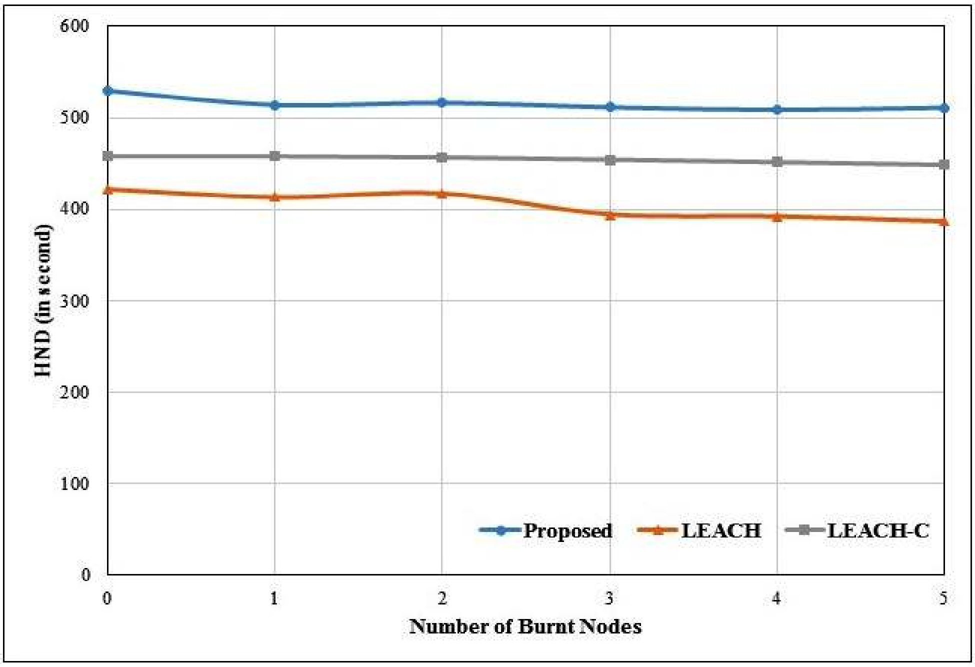

Figure 3-21. HND for different numbers of burnt nodes.

3.6 Summary

This chapter has presented the effect of choosing CHs which will destroy on the network performance of WSN in emergency applications such as forest fire monitoring. Three approaches are compared in this chapter, namely, the proposed approach, LEACH, and LEACH-C. The proposed approach considers the node health status in choosing a CH and uses the random probability as in LEACH. Moreover, it applies multi-hop communication to increase scalability and energy efficiency. The performance metrics which are measured in this comparison are data received, energy consumed, packet delivery ratio, total alive nodes, first node destroys (FND), and half node destroys (HND). Simulation results prove that when there is no fire in the network, the proposed approach outperforms LEACH and LEACH-C with regards to data received, energy consumed, total alive nodes, FND and HND due to multi-hop communication. Furthermore, when the number of burnt nodes varies, there is a stabilisation in data received, energy consumed, PDR, energy efficiency, FND, and HND since the proposed approach refrains from selecting danger nodes as CHs.

Chapter 4: Energy Efficient and Safe Status Distributed Grid Clustering

4.1 Introduction

LEACH is a leading routing protocol for clustering Wireless Sensor Networks (WSN)[58]. It is a distributive routing in which a cluster formation is accomplished locally without any control from the BS. In this approach, every node generates a random probability and compares its probability with a threshold probability, which is formulated in equation 3-1. In the event that the probability of the node is higher than the threshold probability, it can be a Cluster Head (CH). On the other hand, it sets itself up as a Cluster Member (CM). In the data delivery phase, every CM sends its data in a time slot. LEACH adopts the TDMA technique to avoid intra-communication interference and collisions among data packets. A TDMA frame contains some slots with equal size. Total slots depend on the number of CMs in a cluster. For instance, suppose there are five CMs in the cluster with the duration of one slot is 0.1 second, and the duration of data delivery is ten seconds. In this case, one TDMA frame has 0.5 second long, and there will be twenty TDMA frames or twenty slots from every CM in this cluster. In short, total time slots which have to be sent increases as the total CM in the cluster reduces.

Selecting a CH using a random probability of the node as in LEACH can lead to the randomness of CH's positions in the network. Figure 4-1 shows the position of CHs in the network for two cases. Figure 4-1(A) illustrates CH's locations which are distributed uniformly. This figure is an ideal condition of LEACH, and every CH has almost the same number of CMs. In Figure 4-1(B), there are three adjacent CHs (CH1, CH2, and CH3) sharing CMs. On the other hand, some CHs (CH4, CH5, and CH6) are far away from others. These conditions can lead to the unbalanced number of CMs in CHs. Adjacent CHs possess smaller total CMs than those which are far away. CMs in these CHs will transmit more data packets to the CH than other CMs, and as a result, their energy will drop quickly.

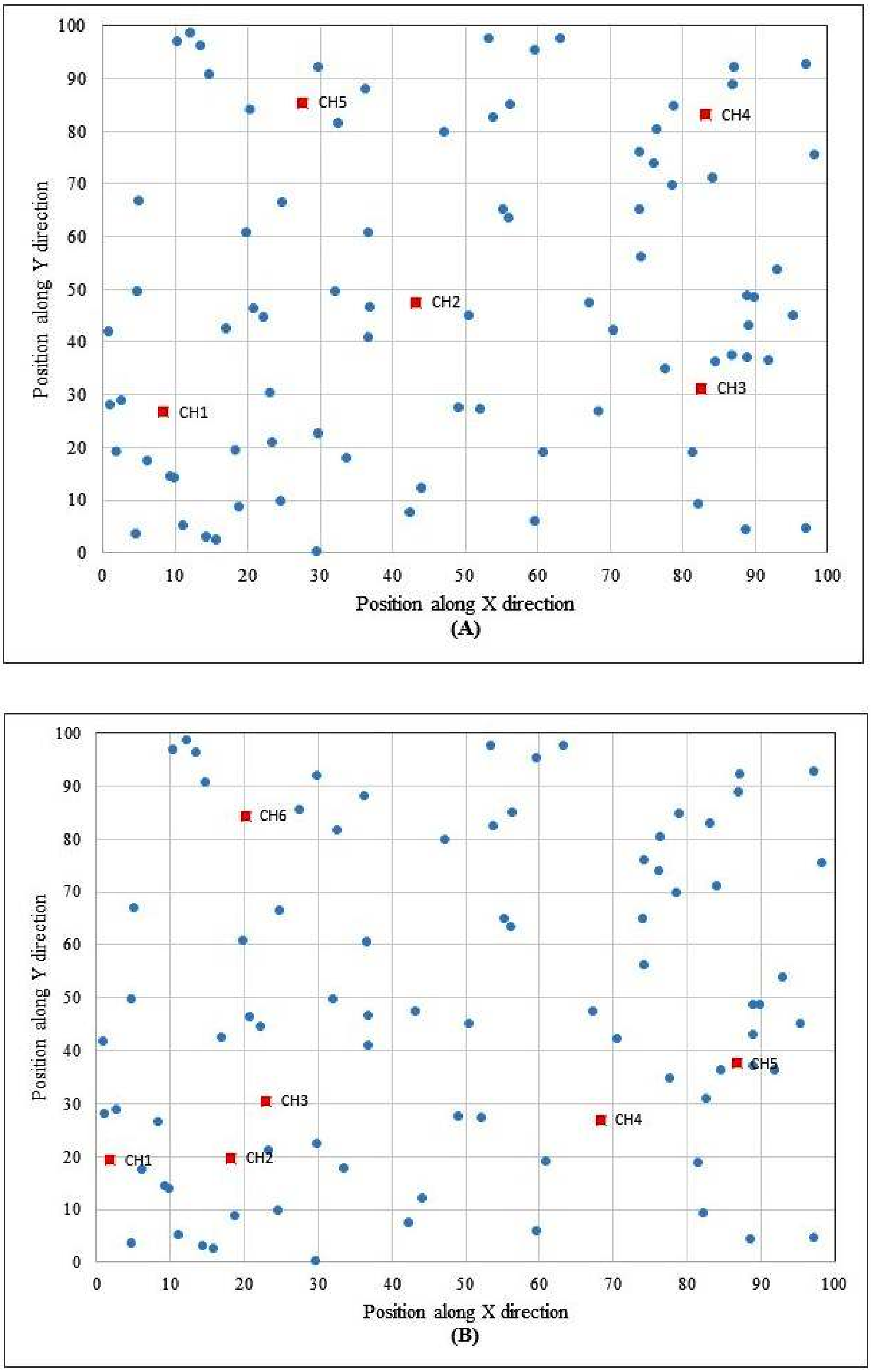

Figure 4-1. The positions of CHs in the network at two instances.

LEACH has verified analytically in [58] that the optimal number of CHs, in which energy consumed is the most efficient, is three up to five per cent of the total number of nodes. Moreover, works in [115] have demonstrated that the total of CHs should be between three and eight, while in [45], has revealed that it should be around two to four. Although LEACH also establishes the expected number of CHs is five, it fails to maintain the optimal number of CHs. Figure 4-2 demonstrates the total CHs in every round using LEACH. Here, the total number of nodes are hundred and the simulation time is seven hundred seconds. As shown in Figure 4-2, total CHs in every round fluctuate from one to thirteen. These variation can lead to unbalanced energy consumption in every round.

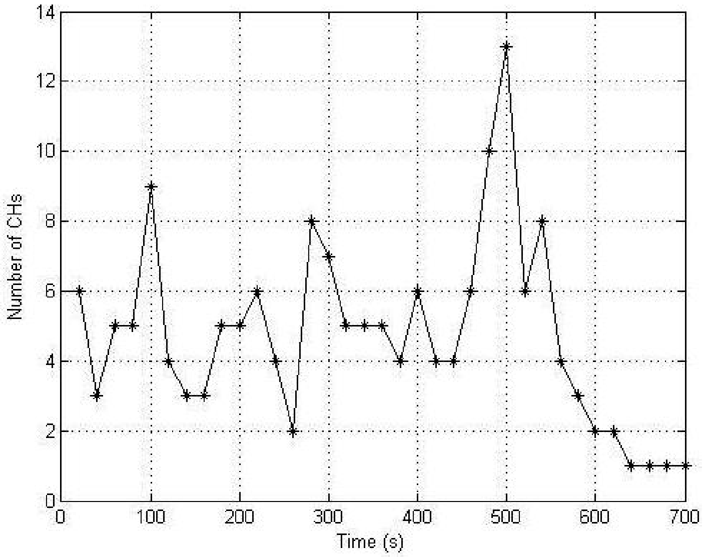

Figure 4-2. The variation of total CHs with the time in LEACH.

To overcome the limitations in LEACH concerning the variation of number of CHs and random position of CHs, a grid-based clustering for energy efficiency is proposed. Clustering is performed locally, and the nearest nodes to the centre of grids are elected as CHs in the first round. Furthermore, the health status of nodes is taken into account in choosing a CH, and therefore the proposed approach can be implemented in emergency applications. The optimal number of grids is involved which is around three until five per cent of total nodes. In the second round onward, CHs are chosen by the previous CHs according to their remaining energy and distance to the centre. In doing so, the total CHs are constant, and the distribution of CHs is almost uniform.

This chapter is begun by introducing weaknesses founded in LEACH and the basic idea of the proposed approach. Following this, other works focusing on the grid clustering and several routing with a fixed number of CHs are explored in section 4.2. The brief explanation of the proposed algorithm is presented in section 4.3. As in chapter three, parameters and scenarios of the simulation are described in section 4.4. Additionally, this section explains performance metrics in the simulation. Based on those parameters and scenarios, the simulation is run, and the results are given in section 4.5. This section also discusses findings obtained from the simulation. The last section is section 4.6 summarising chapter four of the thesis.

4.2 Related Works

As discussed in chapter two, clustering is a promising technique for WSN due to its capability to prolong network lifetime[2][28]. One of the clustering approaches that have been implemented in WSN is a grid clustering. This section will explore some grid-based clustering routings which have been performed in WSN. Moreover, this section reviews several routing techniques with a constant number of CHs in every round.

A grid clustering routing (GROUP) is introduced by authors in [126] for forest fire applications. There are two nodes involved in choosing CHs in this approach, namely, a primary sink (PS) and a grid seed (GS). PS, which is usually located in the centre of the network, establishes a grid creation by sending a GS-election command to the GS. Meanwhile, the GS is a node placed at the intersection point of the grid with R size and has more energy than other nodes in that location. A CH in GROUP is the nearest node to the GS. A grid-based coordinate routing protocol, which is depending on the flooding technique, is proposed by Akl et al. in [110]. Initially, the size of the grid is defined by the user and should be less or equal to the maximum transmission range of the node. Following this, the ID of nodes are assigned randomly, and in every grid, a node with the highest ID is selected as a CH. If the percentage of CH's energy is equal or lower than 25%, the CH will be replaced by a node with the second highest ID. At the beginning of the data delivery phase, a query message is broadcasted by the BS to every CH in the network. CHs forward this message to other CHs. Non-CHs in this phase remain in the sleep mode to save their energy. Data from the source is transmitted via CHs until it reaches the BS. Authors in [127] introduced a hierarchical routing with grid-based structure. There are three phases in this approach; a gridding phase, a clustering formation phase, and a steady state phase. In the gridding phase, the network is divided into grids in which its total number depends on the average energy of nodes. Following this, the BS determines CMs of every grid and the next CHs, which are selected according to the round-robin technique. When the average energy of all nodes is between two-thirds and one-third of the initial energy, a grid CH (GCH) executes the second level splitting of the network into four grids. Finally, as the average energy falls to lower than one-third, the third level is begun with one grid. Another grid clustering routing according to centralise control is provided in [111]. This protocol is named as centralised energy aware grid clustering protocol (EAGC) in which a threshold distance, a maximum direct transmission distance between cluster head and cluster member, establishes the size of the grid. Energy model from LEACH is analysed to get the threshold distance. Here, the grid size is equal to $d_{threshold}/\sqrt{2}$. After determining the grid size, the BS picks nodes out with the highest residual energy as CHs in every cluster. Following this, data packets are sent from CMs to the CH according to the TDMA schedule. If the distance from a CH to the BS is higher than the threshold distance, multi-hop communication is utilised to reduce energy consumed. On contrast, data packets are transmitted directly to the BS.

The works in [58] argued that there is an optimal number of the clusters to enhance energy efficiency in the network. Additionally, if the routing algorithm can maintain the optimal total CHs in every round, network lifetime improves significantly. Therefore, this leads to the development of the routing approach with a constant number of CH. LEACH-C, which is a version of LEACH proposed by Heinzelman [58], is a centralised routing with a fixed total CH. To begin with, every node sends a message to the BS with reference to its position and remaining energy. After receiving these messages, the simulated annealing algorithm is accomplished by the BS to group nodes into clusters. In every cluster, if the energy of a node is higher than the average energy of all nodes, the node has a chance to become a CH. The transmission of data packets according to the TDMA schedule is the next step of LEACH-C. All data from CMs have to be delivered to the CMs before these data are forwarded to the BS. As in LEACH, LEACH-C utilises full aggregation. LEACH-B (Low Energy Adaptive Clustering Hierarchy-Balance) [128] is another clustering routing which is adding a second election of CH to make an optimal total CHs in every round. If the total CH has not achieved the optimal value yet, a timer is generated. A node with the highest remaining energy has the shortest timer. Then, the node declares its status as a CH and informs other nodes about its status. After getting an optimal number of CHs, the data delivery phase as in LEACH starts. Authors in [129] introduced a centralised clustering routing using the Fuzzy C-means algorithm. This protocol has the same approach as LEACH-C, but instead of using the simulated annealing algorithm, it applies Fuzzy C-means. An improvement of Fuzzy C-means clustering is suggested by Lee in [112]. It is a hierarchical routing that implements centralised gridding at upper levels and a distributed gridding at lower levels. Every node in the network is categorised into layer-0 nodes, layer-1 CHs, layer-2 grid heads, and the BS. Cluster formation in layer-0 and cluster head election are done using Fuzzy C-means as in [129], while grid heads are chosen using the LEACH approach. After picking CHs and grid heads, data transmission is started. Data packets are travelled from nodes to the CHs, then from CHs to cluster grids, and finally from cluster grids to the BS.

4.3 The Proposed Approach

In this section, a proposed routing protocol based on grid clustering is explained. Before exploring the detail of the proposed method, the definition of a grid-based clustering is clarified here. The term grid-based clustering is used by Saxena in [114] to refer to the process that classifies the space into a finite number of clusters forming a grid structure. Grid clustering offers several benefits, such as a low processing time, no need of the distance computation, and easiness in deciding neighbouring clusters[114]. Firstly, this method defines a set of grid cells. Following this, every object is signed to the appropriate grid cell and then, the density of grids is calculated. Here, it is assumed that every node are equipped with Global Position System (GPS) in order to know their location. If there are some cells that have lower densities than a certain threshold, these cells should be deleted. After this, all cells are reconfigured to complete final grid cells.

A grid-based clustering for energy efficiency is a proposed routing which consists of two phases: a cluster formation phase and a data delivery phase. The purpose of the cluster formation phase is to design a grid structure, opt for cluster heads in every grid, and sign every node to the grid. Meanwhile, data packets are sent to the destination effectively in the data delivery phase. The following subsection describes an in-depth study of the proposed approach.

4.3.1 Cluster Formation Phase

At the commencement of the cluster formation phase, the proposed approach defines the number of grids in the network, which is depending on the total number of sensor nodes. As stated in section 4.1, the best number of CHs to achieve the optimal energy efficiency is three until five per cent of the total sensor nodes. Here, for per cent is set up for this approach. For instance, if a hundred nodes are deployed in the network, four is chosen as the number of grids. Following this, in every cluster, the centre of the cluster is defined as a reference point that is used to measure how far the position of nodes to the centre of its cluster. Figure 4-3 displays a network with four grids and their centres.

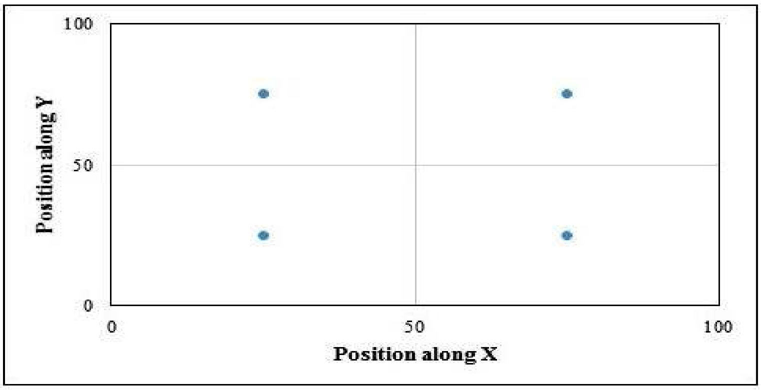

Figure 4-3. A network with four grids.

Figure 4-4 summarises the algorithm of the cluster formation phase in the first round. After defining the number of clusters and the centre of every cluster, a node calculates its distance to the centres of every cluster, which is denoted as d_{centre}. The node, then, decides to join to the cluster with the lowest d_{centre}. For instance, if there are four clusters in the network and the lowest d_{centre} is a distance to cluster 1, the node will choose cluster 1 as its cluster. The next step is to check whether d_{centre} is smaller than r or not, which is a sensing range of the sensor node. If that is true, the node declares itself as a candidate CH by broadcasting an ADVERTISEMENT (ADV) message, as pointed out in Figure 4-5. The message consists of four fields: a message type, a candidate node's ID, a d_{centre} of the node, and a zone's ID. Here, the first field is the type of message, which is an ADV message. The second field is the ID of node broadcasting the message. The third and the fourth fields are the distance from the node to the centre and the ID of cluster respectively. Both CHs and CMs have to wait for the ADV messages from other CHs.

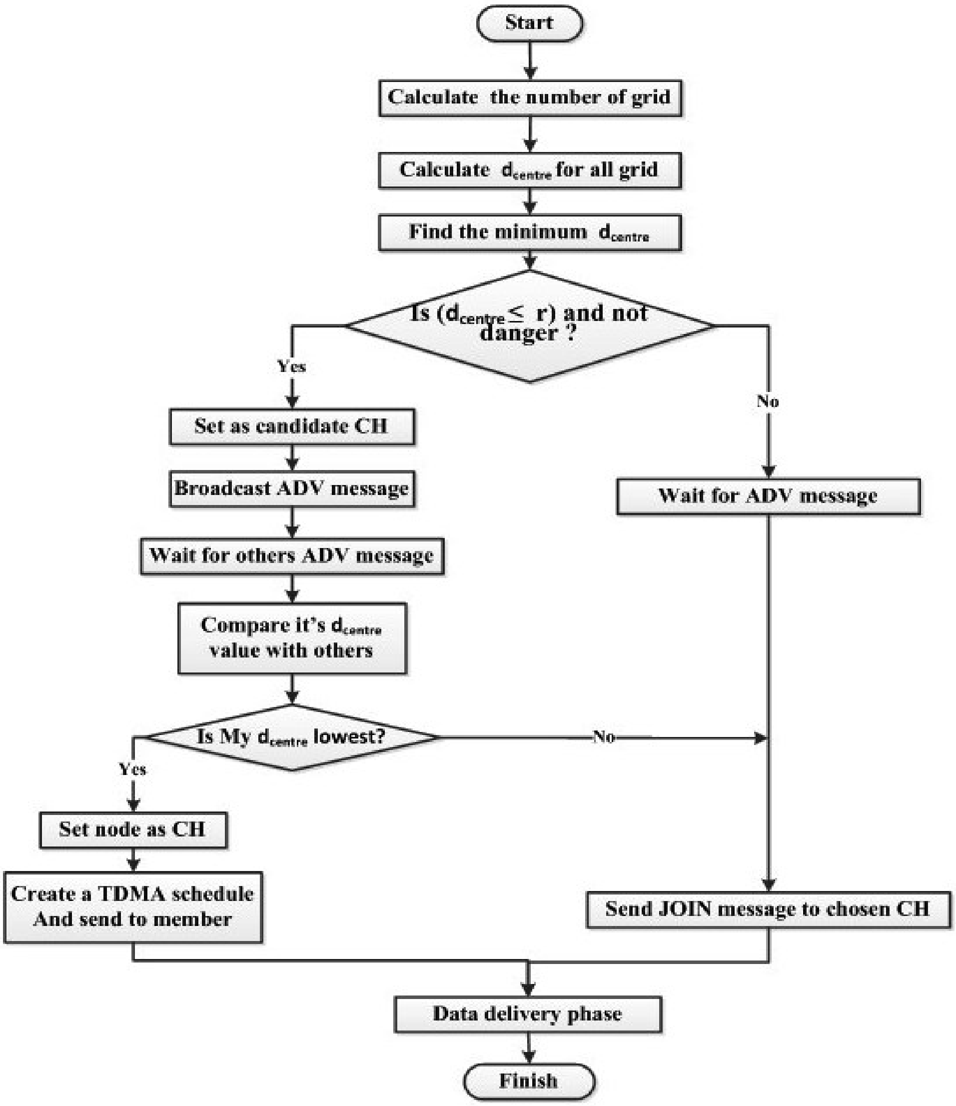

Figure 4-4. The flowchart of the cluster formation phase in the first round.

Message Type	Candidate Node's ID	d_{centre} of Node	Zone's ID

Figure 4-5. The format of the advertisement message.

Once a candidate accepts all the ADV messages from other candidates with the same zone ID, it compares its d_{centre} with others and finds the minimum one. If its d_{centre} is the lowest, it determines itself as a CH. Conversely, it sets itself up as a CM. At the same time, when a CM receives the ADV messages from the candidates, it finds the minimum d_{centre}, and chooses the candidate with the lowest d_{centre} as its CH. After seeing the best CH, the CM sends a JOIN-REQUEST message to its CH with a format as in Figure 4-6. Both this message and the advertisement message have the same information in the first and the last field. The ID of the node and the distance of a node to the BS are in the second and the third field. Meanwhile, the current remaining energy of the node is pointed out in the fourth filed. Subsequently, the CH determines a TDMA schedule which is a sequence of transmission times of its CMs. This TDMA schedule is disseminated to its CMs.

Message Type	Node’s ID	Distance to the BS	Node’s Energy	Zone’s ID

Figure 4-6. The format of the joint-request message.

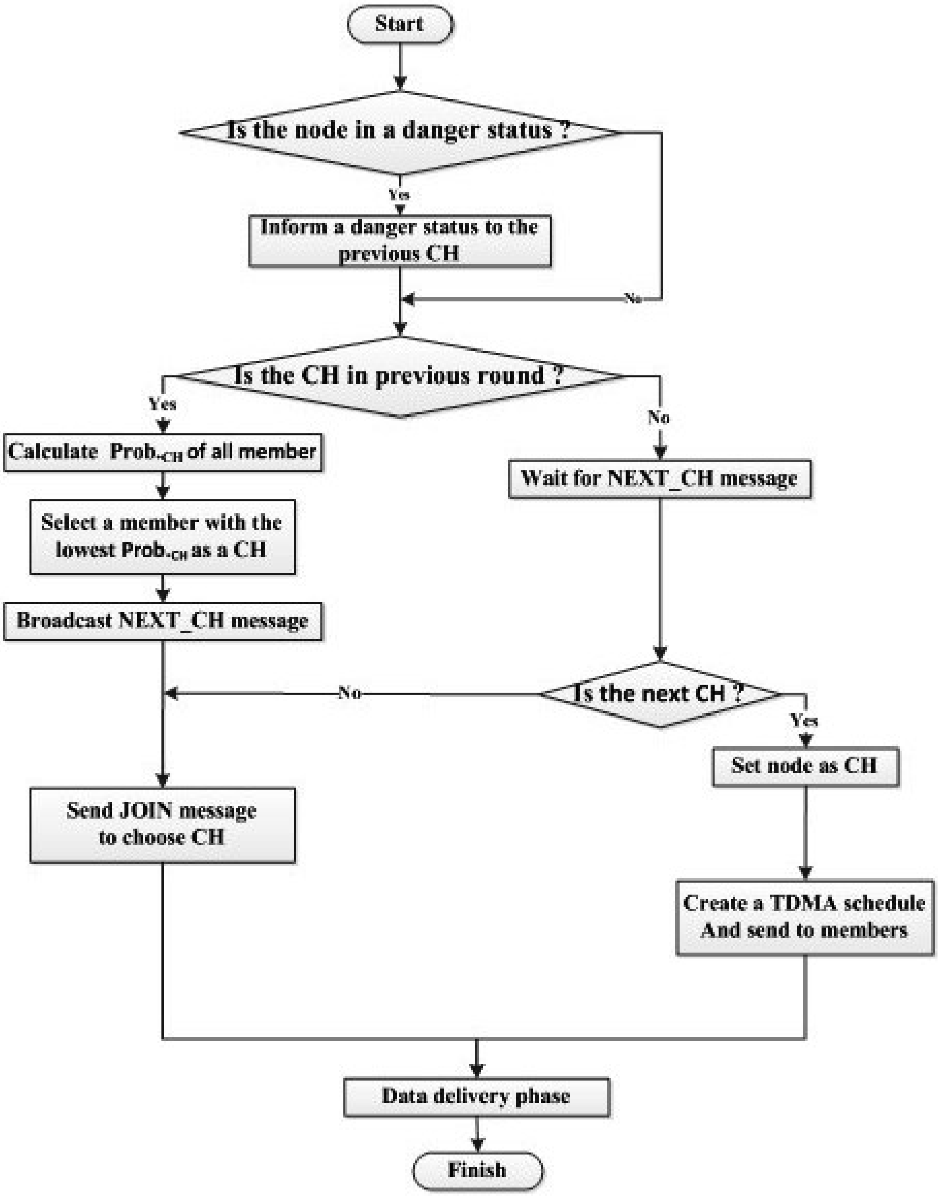

Figure 4-7. The flowchart of the cluster formation phase in the second round onward.

In the second round onward, the cluster formation phase has different steps. Figure 4-7 points out the cluster formation phase in this round. At the beginning of the second round onward, every CM has to check its status, whether it is in danger or safe status. If its status is a danger, it sends this information to the previous CH with the format as presented in Figure 4-8. The CH of the prior round has an authority to select a CH in the second round onward. Firstly, if a node is a CH in the previous round, it calculates probabilities of CMs to become a CH, using the equation below:

$$P_{CH} = \left(1 - \frac{E_{remaining}}{E_{initial}}\right)\left(\frac{d_{centre} - d_{centre\_min}}{d_{centre\_max} - d_{centre\_min}}\right)P_{status} \qquad 4\text{-}1$$

Here, P_{CH} is a probability of a node to become a CH. Also, $E_{initial}$ and $E_{remaining}$ are the initial and residual energy of the node. The distance of the node to the centre of the grid is denoted as d_{centre}, while, d_{centre_min}, and d_{centre_max} are the minimum and maximum of d_{centre}. Meanwhile, P_{status} refers to the health status of the node, which is 0 for the danger node and 1 for the safe node. After choosing a node with the lowest P_{CH} as a CH for this round, the CH in the previous round broadcasts a message containing information about a CH for this round. The format of the message is displayed in Figure 4-9. This message consists of a message type, which is a NEXT_CH, the ID of the node, and the ID of the cluster.

Message Type	Node's ID	Node's status	Zone's ID

Figure 4-8. The format of the status message.

Message Type	The current CH's ID	Zone's ID

Figure 4-9. The format of the next CH message.

A CM receiving this message checks whether its ID matches the ID of the current CH. When its ID is equal to the current CH's ID, the node becomes a CH in this round and creates a TDMA schedule as in the first round. On the other hand, if it does not match, the node sends the joint-request message to the current CH. Also, the CH in the previous round sets itself as a CM in this round.

4.3.2 Data Delivery Phase

The data delivery phase begins when CMs send data to their CHs. It has the same methods as in section 3.3.2. After receiving the TDMA schedule from the CH, every CM send data to its CH alternatively according to the TDMA slot. By doing this, collisions among packets can be minimised. Since the CH fully aggregates packets from its CMs, the total packet sent to the BS is minimum. Therefore, there is only a small amount of energy consumed to transmit packets from the CH to the BS.

4.4 Performance Evaluation

The performance evaluation of the proposed approach is analysed by Network Simulator 2 (NS2), a discrete event simulator for the wired and wireless network. Here, based on the proposed algorithm, a grid routing protocol for improving energy efficiency is developed in NS2 environment. In this section, two aspects in running the simulation, which are parameters and scenarios, are explored. Following this, the metrics used to examine the proposed approach's performance are presented, and its quality is compared with other approaches such as LEACH and LEACH-C. LEACH is chosen since it is a fundamental of distributive clustering while LEACH-C is a clustering with constant total CHs.

4.4.1 Parameters of Simulation

As in the previous chapter, parameters of the simulation in this experiment can be classified into two categories: radio and network parameters. Table 4-1 provides all radio parameters in this simulation. Four parameters relate to the energy model, four parameters belong to radio communication, and two parameters are for antenna specification. The energy model from LEACH is adopted, and all values in this experiment use the same values as in the LEACH simulation. Wavelength, frequency, and bandwidth of signal are 0,328m, 914MHz, and 1Mbps respectively. Here, it is assumed that the loss of this radio system is one. Moreover, it is supposed that the height of the receiver and transmitter antenna is 1.5m.

A total number of nodes deployed in the simulation is a hundred, as displayed in Table 4-2. The area of the simulation is 100x100 meter square, and the BS is located outside the area. The simulation time is eight hundred since this interval is enough time to get stable results. The data packet has 500 bytes long, and the interface of queue applies the DropTail type with 100 bit long.

Table 4-1. The radio parameters in the simulation.

Parameters	**Values**
Radio energy for electronic processing (E_{elect})	50 nJ/bit
Radio energy for free space propagation (ε_{fs})	10 pJ/bit/m2
Radio energy for multi-path propagation (ε_{mp})	0,0013 pJ/bit/m4
System loss (L)	1
Antenna height in transmitter and receiver (h_t, h_r)	1,5m
The cross-over distance ($d_{crossover}$)	86,3m
Bandwidth (B)	1 Mbps
Radio frequency (f)	914 MHz
Wavelength of signal (λ)	0,328m
Initial Energy (Joule)	2

Table 4-2. The network parameters in the simulation.

Parameters	**Values**
Network area	100 x 100 m2
Location of BS	50, 175
Number of Nodes	100
Simulation Time	800 second
Size of packet	500 bytes
Interface queue type	Drop Tail/PriQueue
Queue length	100

4.4.2 Scenarios of Simulation

There are two scenarios in this simulation: no burnt node and one to five burnt nodes. In LEACH and LEACH-C, all burnt nodes are those selecting as CHs. In contrast, since the proposed considers the health status of node in choosing the CH, CHs in this approach never selected as CHs. As a result, five burn nodes mean that five CHs are burnt in LEACH and LEACH-C while in the proposed approach, it means five nodes are burnt. For both scenarios, there are ten different topologies with ten repetitions. The first scenario is employed to analyse the performance of the proposed approach in a normal situation, where there are no burnt nodes in the network. The second one is performed to study the effect of total burnt nodes to the performance of the proposed approach, LEACH, and LEACH-C. Burnt nodes are those close to the centre of the grid. The danger statute of nodes is activated randomly in the second round, and they are dead in the next round.

4.4.3 Performance Metrics

The performance metrics are used to compare the proposed approach with LEACH and LEACH-C. These metrics are listed below.

- Data received: It represents the total packets received in the BS over the simulation time.
- Alive node: This metric demonstrates how many nodes that are not dead due to energy drained or burnt off fire over the simulation time.
- Energy consumed: It relates to the total energy consumed by nodes over the simulation time.
- First Node Destroys (FND): It is the period from the simulation is started until the death of the first node as energy drained.
- Half Node Destroys (HND): It is the period from the simulation is started until half of the total nodes is dead due to energy drain.
- Packet delivery ratio: The ratio of total packets collected by the BS to those sent by sources is called PDR.

4.5 Simulation Results and Discussion

Having provided the parameters, scenarios, and performance metrics of the simulation, this section presents the results of the simulation comparing the proposed approach with LEACH and LEACH-C. All of the results are based on the average value after running ten times of the simulation.

4.5.1 Data Received

The total packets received in the BS over the simulation time is provided in Figure 4-10. All graphs reveal that there are slight increases in packets collected in the BS as the simulation time rises. LEACH-C has the highest packet received at the end of the simulation, which is around 60 thousand. Since this approach applied the simulated annealing algorithm in grouping sensor nodes in the network, the best formation of clusters can be fulfilled. Hence, LEACH-C transmits more data than others. The proposed approach experiences the same trend as LEACH-C, but it receives around 50 thousand packets, which is the second one. Meanwhile, LEACH, applying randomness in opting for a CH, provides only around 40 thousand packets, which is the lowest one. Here, the proposed approach outperforms LEACH because the formation of clusters in the proposed approach is more uniform than LEACH.

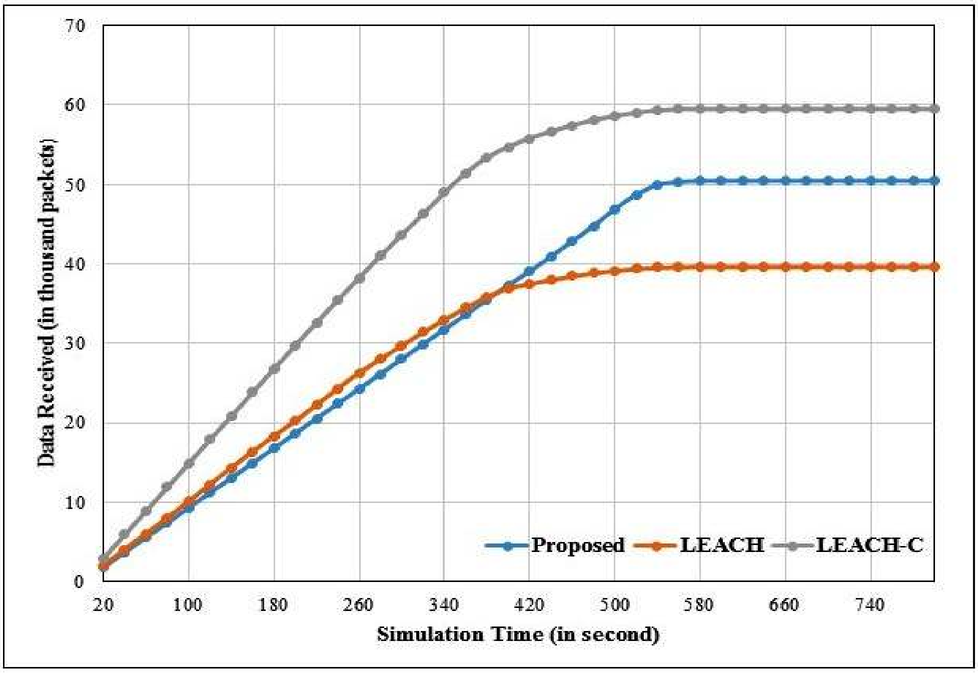

Figure 4-10. Total data received when no burnt nodes vs the simulation time.

Figure 4-11 indicates the effect of different numbers of burnt nodes on data received in the BS, for the proposed approach, LEACH and LEACH-C. These data are collected in the BS in the third round since burnt nodes occur between the second and the third round. There is a slight fall in data received for LEACH while in the proposed approach, data received stays constant for all numbers of burnt nodes. In the proposed approach, if the status of the node is in danger, its probability to become a CH is zero. Therefore, the previous CHs only choose nodes which are not in the danger statuses. Consequently, the total CH is constant in the optimal value, and the burnt nodes are sensor nodes which are not CHs. Data which are not accepted in the BS are only those from burnt cluster members.

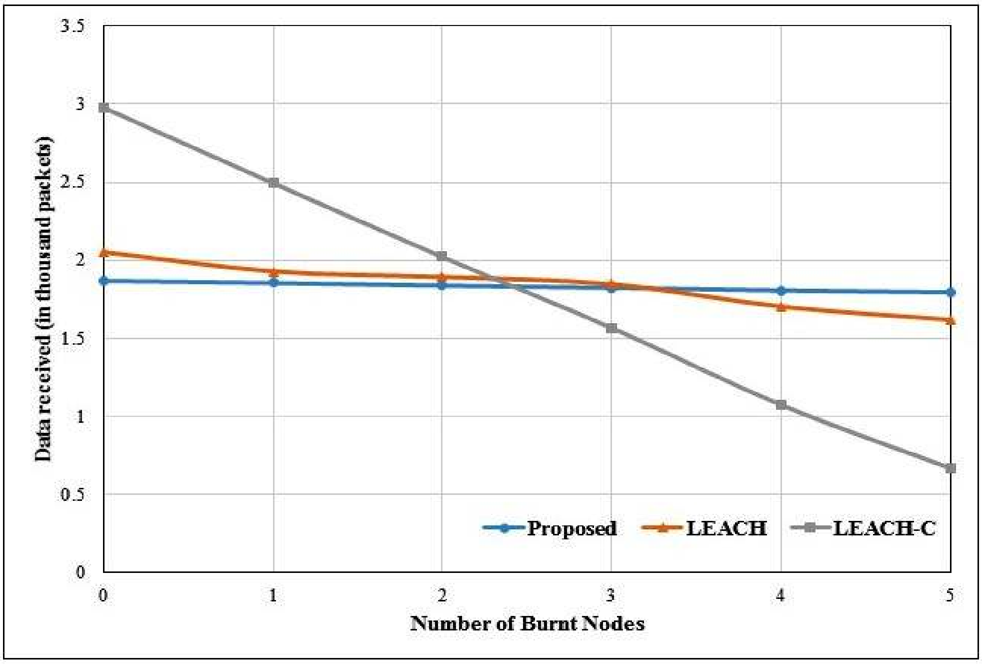

Figure 4-11. Total data received vs numbers of burnt nodes.

4.5.2 Energy Consumed

The expenditure of energy, which is the main issue in WSN, is one of the simulation results observed in this experiment. Figure 4-12 plots the total energy consumed in the network when the simulation time goes up from zero to eight hundred. For all three approaches, there is a gradual rise in the total energy expenditure from 20 to around 550 seconds, and it remains unchanging after 550 seconds. The rate of energy spent of the proposed approach is the lowest because it has the optimal number of CHs in every round and considers the remaining energy of the nodes and their distance to the centre of the grid as parameters in choosing a CH. Although the rate of packets arrived in the BS between LEACH and the proposed approach are same, LEACH depletes more energy than the proposed approach because of an unstable number of the total CHs in the network. For instance, when the number of total CHs in lower or higher than the optimal number, LEACH spends more energy than LEACH-C and the proposed approach. Another method, LEACH-C, has the same speed of energy consumed as LEACH even though LEACH-C has a fix total CH. The possible explanation from this case is that

LEACH-C spends more energy in the cluster formation phase than the proposed approach due to the centralised cluster formation in which every sensor node has to inform its position to the BS directly at the beginning of the round to design effective clusters and choose CHs.

The variation of energy expenditure from every node for different numbers of burnt nodes is indicated in Figure 4-13. The proposed approach has constant energy consumption in the third round while LEACH and LEACH-C experience different patterns. There are several explanations from these results. In the proposed approach, there is an insignificant drop in energy drained because all loss energy comes only from burnt cluster members. In LEACH-C, because all burnt nodes are CHs, the loss of energy consumed goes down significantly. Indeed, this result reveals that data transmission from the CH to the BS in LEACH-C depletes the most energy.

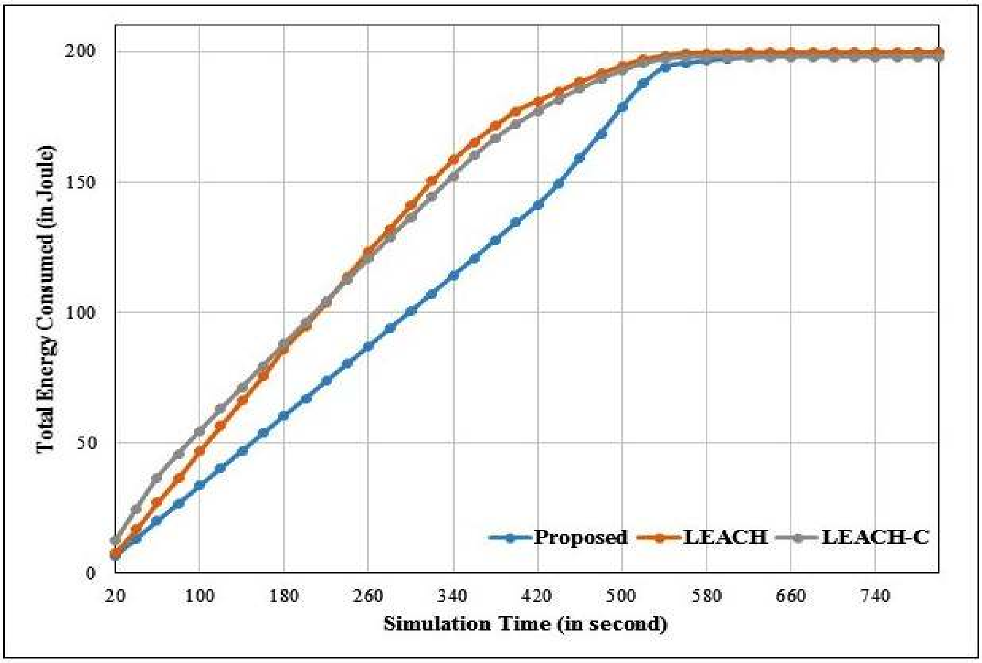

Figure 4-12. Total energy consumed with no burnt nodes vs the simulation time.

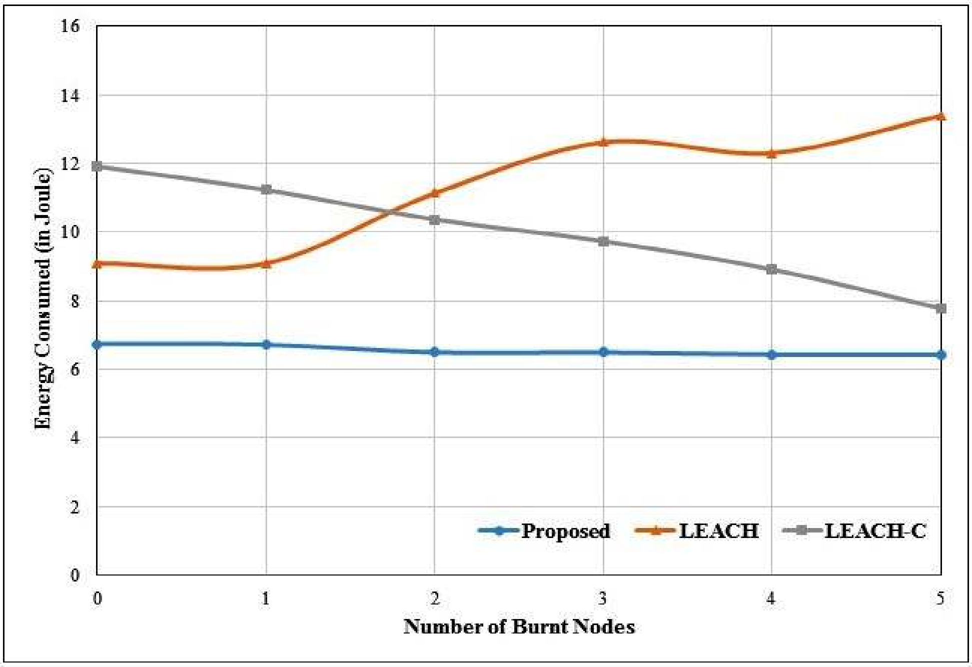

Figure 4-13. Energy consumed vs numbers of burnt nodes.

4.5.3 Packet Delivery Ratio (PDR)

Figure 4-14 provides packet delivery ratios for different numbers of burnt nodes. PDR of the proposed approach when there are no burnt nodes is the highest, which is around 0.98. In the proposed approach, there is a little collision in transmitting data from the CM to the CH or from the CH to the BS since the distribution of sensor node is fixed and uniform, as illustrated in Figure 4-15 (A) and (B). It is clear that there are no CHs closer to each other. This condition helps to minimise packet collision. Besides, every node decides itself to join any clusters in the first round, which is based on the grid clustering algorithm, and it sets the zone's code up to avoid interference among sensor nodes in adjacent clusters. Therefore, unlike LEACH and LEACH-C, there are no nodes that do not have a CH. Sending data directly to the BS has a higher probability of collision than sending to the CH. When the number of burnt nodes goes up, the number of lost packets is minimal. This result may be clarified by the fact that including the health status of the node as one of the probabilities in choosing a CH can minimise loss of packets since these lost packets only come from the burnt CMs.

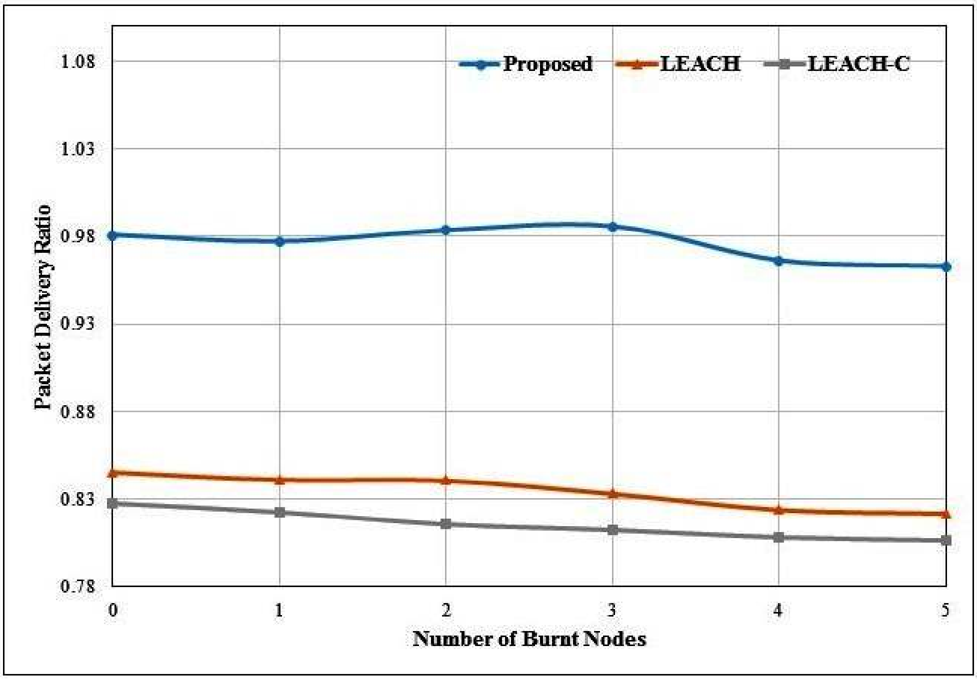

Figure 4-14. Packet delivery ratio vs numbers of burnt nodes.

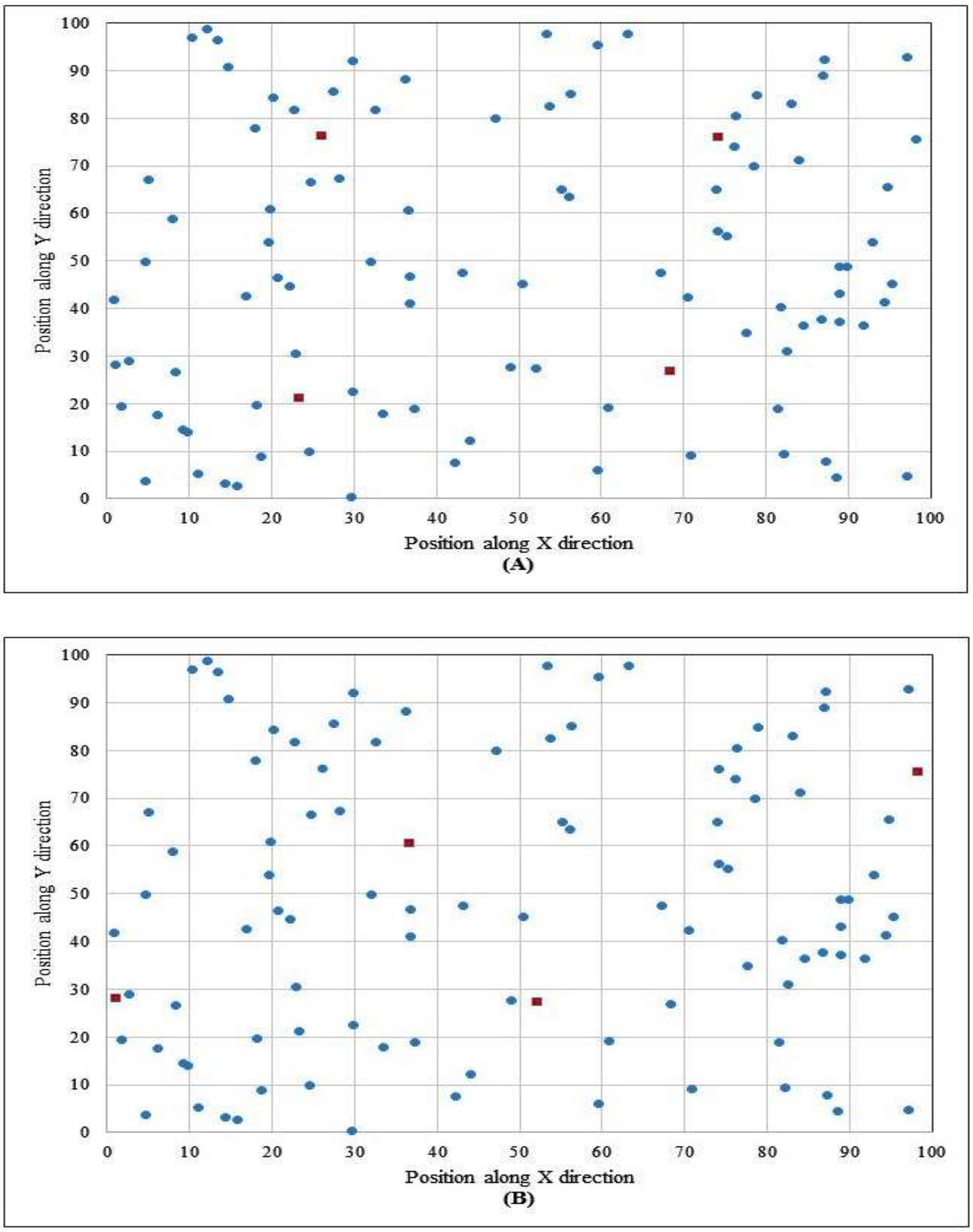

Figure 4-15. The positions of CHs and CMs in the network in the 1st round (A) and 15th round (B).

4.5.4 Energy Efficiency

Figure 4-16 plots three graphs in respect of energy efficiency for the proposed approach, LEACH, and LEACH-C when the number of burnt nodes vary from one to five. Generally, the proposed approach has the highest energy efficiency, which is around 279 packets per joule, and there is no significant change in this efficiency for different numbers of burnt nodes. The results can be explained by the fact that in the proposed approach, including the node health status as a parameter in choosing a CH can avoid selecting a burnt node as a CH. Therefore, the number of lost packets is minimal, and energy efficiency of the network is almost stable.

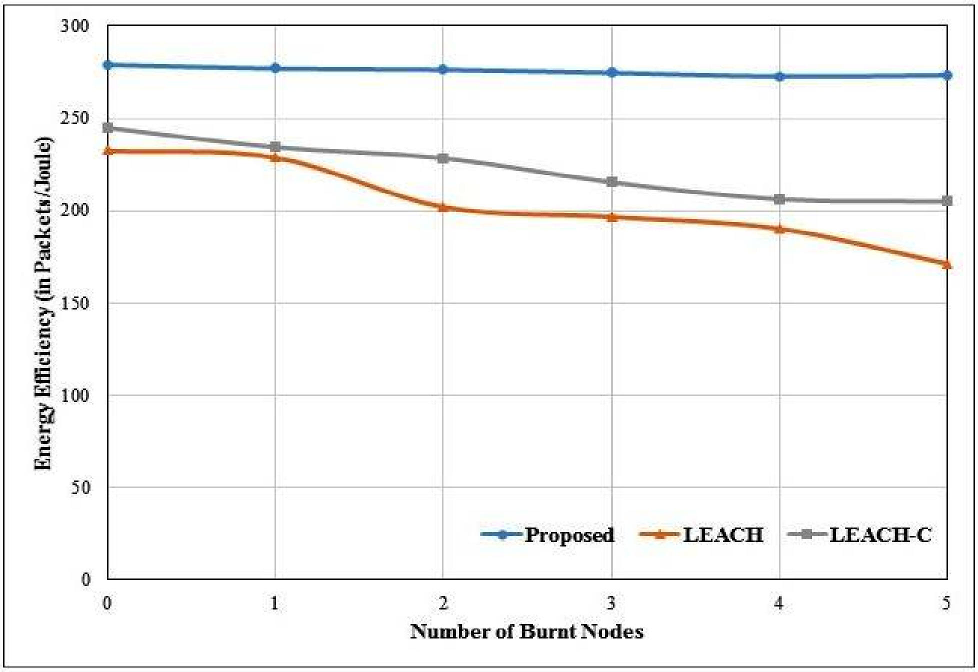

Figure 4-16. Energy efficiency vs numbers of burnt nodes.

4.5.5 Total Alive Nodes

Total alive nodes, which is proportional to energy consumed, are displayed in Figure 4-17. Generally, the proposed approach can expand the time of alive nodes in the network. As shown in that figure, there are no dead nodes before 360 seconds when the proposed approach is applied. Meanwhile, in LEACH and LEACH-C, all sensor nodes remain alive until 120 and 40 seconds respectively. Here, node lifetime in the proposed approach is three times higher than LEACH. The reason for this improvement is that the proposed approach has the optimal number of CHs and takes into account the residual energy of the node in selecting a CH. In LEACH-C, there are some nodes which are not a member of any CHs. The nodes have to send packets directly to the BS without aggregation, and as a result, they are dying sooner than other sensor nodes.

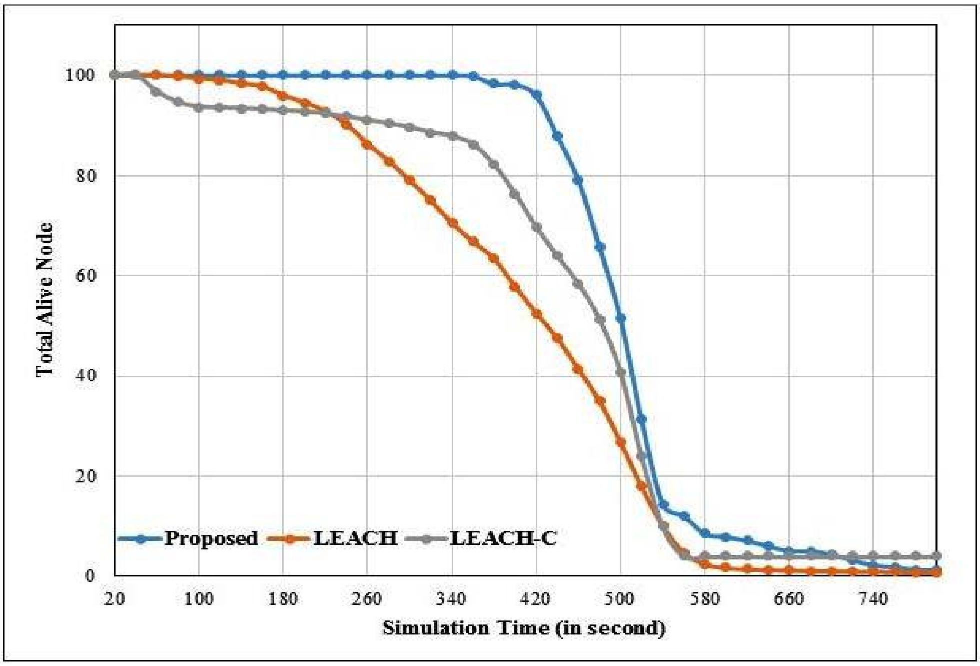

Figure 4-17. Total alive nodes when no burnt node vs the simulation time.

4.5.6 First Node Destroys and Half Node Destroys

Figure 4-18 points out the first node destroy and the half-node destroys for the proposed approach, LEACH, and LEACH-C. It is clear that the proposed approach has the longest FND and HND. There is a growth in FND of around 110 and 150 seconds compared to LEACH and LEACH-C. Additionally, in term of HND, the proposed approach gets around 500 second, which is 10% higher than LEACH and 5% higher than LEACH-C. Again, this result proves that by maintaining the number of CH in the optimal value and choosing a CH based on its residual energy can enhance the FND and HND of the network.

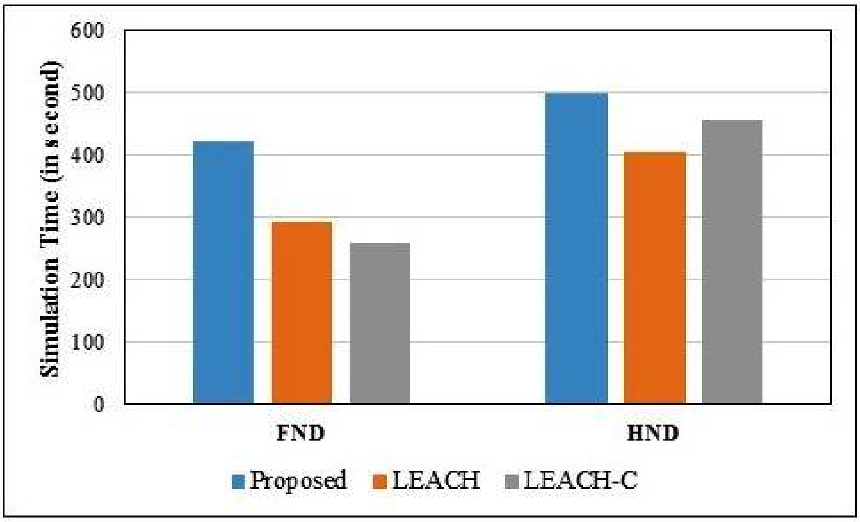

Figure 4-18. FND and HND when no burnt nodes.

Figure 4-19 and Figure 4-20 show the effect of total burnt nodes to FND and HND, respectively. These two cases illustrate that FND and HND of the proposed approach are the highest when the number of burnt nodes are one, two, three, four and five. As stated in the scenario of the simulation, all burnt nodes are placed near the centre of grids. These bring a significant impact on FND of the proposed approach in the network.

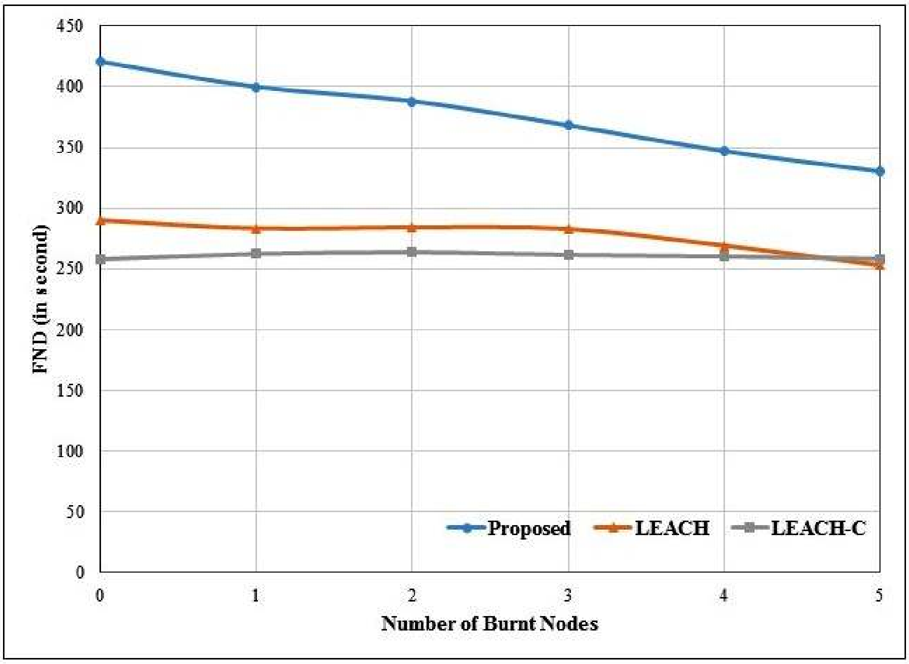

Figure 4-19. FND for different numbers of burnt nodes.

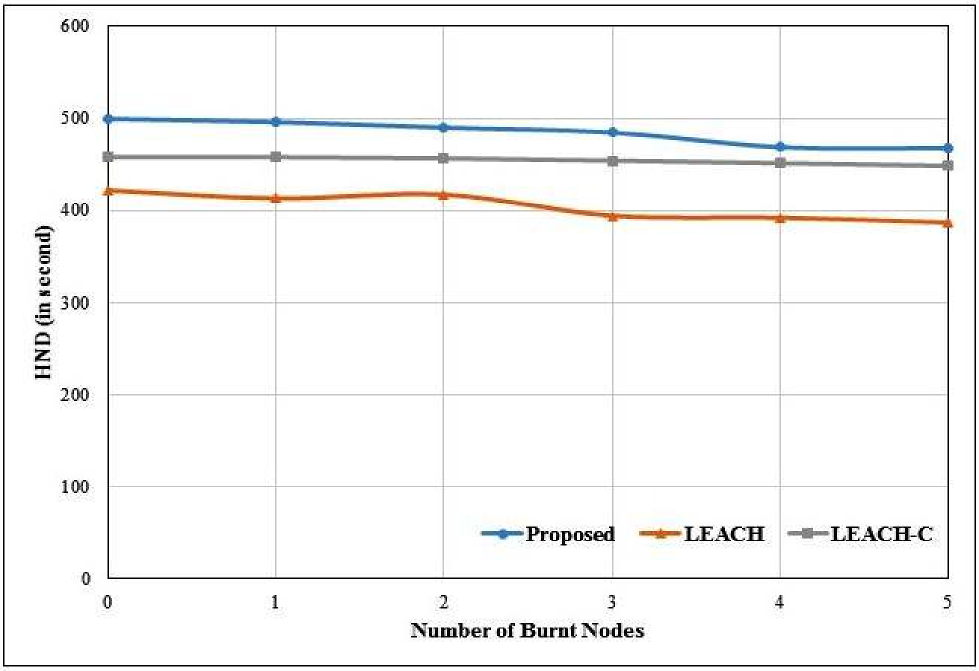

Figure 4-20. HND for different numbers of burnt nodes.

4.6 Summary

A routing based on a grid structure for energy efficiency is presented in this chapter. This approach maintains a constant number of CH in the optimal value and includes the health status of the node in choosing a CH. There are some improvements in connections to packet delivery ratio (PDR), first node destroys, and half node destroys when there are no burnt nodes in the network. PDR of the proposed approach enhances 16% from LEACH and 18% from LEACH-C. The period for first node destroys increases by 45% and 63% compared to LEACH and LEACH-C respectively. Furthermore, in the matter of HND, the proposed approach is higher than LEACH and LEACH-C by 18% and 9%. When the number of burnt nodes varies from one to five, three are no significant changes in energy spent, energy efficiency, and packet delivery ratio. Regarding FND, there is a slight decrease when the number of burnt nodes changes from one to five.

Chapter 5: A Priority Based Grid Time Division Multiple Access (TDMA) MAC

5.1 Introduction

Having proposed a grid clustering routing for energy efficiency in WSN, this chapter focuses on another method to enhance WSN's performance with respect to end-to-end delay and energy consumed, using Medium Access Control (MAC). MAC, a part of link layer protocol, can control the shared medium and manage to transmit and to receive data. Therefore, MAC plays a vital role to reduce collision among data packets. Due to the significant impact of MAC to the network performance, there have been many proposed MAC for wireless network.

As stated in chapter two, MAC can be classified into the type of network: MAC for clustering and non-clustering network. Clustering network has been employed in many monitoring applications such as fire and emergency applications. It is a promising network because of low energy efficiency, simple routing, and extended network lifetime. In clustering network, CHs and CMs work together to deliver data from CMs to the BS. Because of this topology, MAC in clustering network differs than the non-clustering network in many ways. The CHs controlling the network can play an important role in designing an effective MAC. A simple example of MAC for clustering network is Energy-Time Division Multiple Access (E-TDMA) MAC. Basically, it is a slot MAC with a TDMA base. Every CM in the same cluster sends data to the CH following a TDMA frame which is advertised by the CH. This TDMA frame informs when the CM should deliver its data to the CH. In this case, it is assumed that every CM has data to be sent to the destination; therefore, the approach is suitable for monitoring applications. In a specific situation, when monitoring an interest, there exists some important or urgent data to be delivered to the destination as soon as possible. A good example of this condition is some applications for monitoring volcanic or fire activities. When the activities become more significant or danger, data from sensor nodes should be sent with limited time. Here, delay is the primary concern that should be achieved. Hence, a MAC in the clustering network with delay constraint is the main performance of emergency applications.

In emergency applications, delay constraint is an essential factor in network design since emergency data should be delivered in a limited time to the destination to reduce more significant losses to the environment; for instance, in the early warning system such as a tsunami detection, it can prevent many human dead, loss of houses, and environmental damage near to the beach.

This chapter proposes a modified TDMA-MAC to accommodate emergency traffic for emergency applications. The proposed MAC is designed for a clustering network, and therefore, it also supports monitoring applications. The emergency traffic has higher priority than non-emergency traffic to reduce its end to end delay. Moreover, there is no aggregation for this traffic to get original data as well as a low end to end delay regarding emergencies.

There are six sections in this chapter, in which this section is an introduction section. The following section explores some clustering TDMA techniques applying in WSN. The detail of the proposed TDMA approach is described in the third section. The next section provides the performance evaluation method, which consists of scenarios, parameters, assumptions, and performance metrics of the simulation. All simulation results are presented in the fifth section, along with their discussions. The last section is the conclusion, concluding this chapter and providing future works of this research.

5.2 Related Works

There have been many proposed MAC for tackling limitations of WSN. But mostly, they are suitable for the non-clustering network. In this section, some MAC algorithms that have been proposed for clustering network are discussed.

A pioneer of MAC for a clustering network is proposed by Heinzelman in [58]. It adopted a TDMA method and every CM in the same cluster has to be aware of clock synchronisation in transmitting data. When CHs have been chosen, they advertise TDMA schedules to their members. The format of TDMA frames is shown in Figure 5-1. Every CM has followed its schedule managing when a CM has to transmit its data to the CH. After receiving complete data from its member, the CH forwards these messages to the BS. To reduce energy drained, aggregation is performed on data before delivering to the BS. Data are sent in a fixed interval, and there is no priority technique in this MAC since it only designs for monitoring applications.

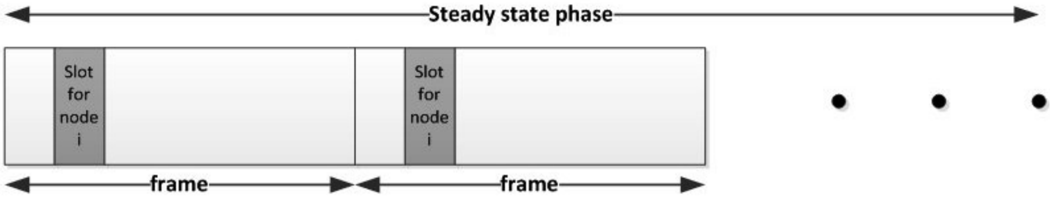

Figure 5-1. Frames of E-TDMA.

A MAC protocol with delay-bounded for Industrial Wireless Sensor Network is introduced by authors in [102]. It supports both monitoring and safety applications in the industrial environment. This protocol is called Slot Stealing Medium Access Control (SS-MAC) because there is a slot stealing process to replace periodic traffic to aperiodic traffic such as critical or emergency traffic. As a result, nodes in this approach are classified into two groups: nodes with emergency and non-emergency traffic. The later nodes must be defined upon the network deployment. As shown in Figure 5-2, the TDMA of SS-MAC has two durations: T_{EIS} and T_S. T_{EIS} is located between two consecutive T_S. T_{EIS} is a duration for an Emergency Indication Sub Slot (EIS), which is used for emergencies. If there is no emergency signal in T_{EIS}, traffic from non-emergency nodes is delivered to the CH according to the TDMA frame. Otherwise, if the EIS is on, this non-emergency traffic must be postponed to be transmitted. Traffic from emergency nodes is placed in the front of the frame. Results show that this MAC can reduce end to end delay for emergency traffic. Unfortunately, since it predefines the location of emergency nodes initially, some critical applications such as forest fire or tsunami detection cannot be implemented using this approach. These applications produce an unpredictable area of urgent traffic.

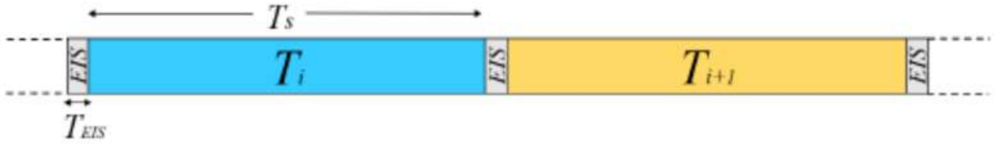

Figure 5-2. The structure of frames of SS-MAC.

Hierarchical Energy-Efficient MAC (HEEMAC) is another MAC based on TDMA which is proposed by Sharma et al. In [52]. Transmission data from CMs to CHs follows a TDMA schedule. However, unlike general TDMA methods, it applies a Hard Threshold (HT) and a Soft Threshold (ST) as in [119] to reduce energy's consumption. To support long-distance communications, it employs multi-hop communications, in which data from CH are forwarded to the next CH if its distance is far away from the BS. Energy's consumption of this approach is optimal due to multi-hop communications and the HT or ST algorithm. Nevertheless, since it only sends data achieving HT and ST, there will be no data collected in the BS if they never reach the soft threshold. Therefore, this approach is not appropriate for monitoring applications.

Another MAC protocol designed for event-driven applications is Bit-map-assisted Energy-Efficient (BMA) MAC [103]. It is based on the TDMA approach and intended for a clustering network. A clustering formation, which is done in the set-up phase, follows LEACH. On the other hand, in the steady-state phase, there are k sessions, and every session contains a contention period, a data transmission period, and an idle period. Initially, a TDMA frame is advertised by a CH to its member, and if a CM has data to be sent, it replies the CH by sending a control message. Following this, a transmission data phase is started, and this CH is called a source node. Alternatively, if there are no data, this slot remains empty, and the node enters the idle period. Due to the contention period in BMAC, there is an extra delay for packets before they are transmitted to the destination. Therefore, emergency applications with limited delay are not implemented to BMAC.

5.3 The Proposed Approach

In the previous section, some MAC based schemes employing TDMA for clustering network was discussed along with some limitations regarding delay and energy constraint. This section introduces a modified MAC TDMA for clustering network, which is suitable to be utilised in an emergency as well as monitoring applications. In emergency applications, delay is a primary concern , while in monitoring applications, the continuity in sending data periodically and energy consumption is the influential quality factors. Since the targeted performance that wants to be accomplished in this proposed MAC is end-to-end delay, before presenting the proposed MAC, a model of end-to-end delay used in this approach is explained.

5.3.1 Modelling of End-to-end Delay

Generally, in data communication networks such as WSN, there are four delays that influence end-to-end delay as a whole[40]:

- Transmission delay (D_{trans}): It is computed by dividing the message size by the bandwidth of the channel.
- Radio propagation delay (D_{prop}): It refers to a time needed for a bit to travel from the source to the destination. This delay is calculated by dividing the distance by the propagation time.
- Signal processing delay (D_{proc}): It refers to a time required to process signal such as coding, decoding, modulation, and etch.
- Queening delay (D_Q): It is a waiting time in the buffer required by a packet before it is processed by a server or node.

The sum of these delays performs end-to-end delay, which is mathematically represented as:

$$D_{ete} = D_{trans} + D_{prop} + D_{proc} + D_q \qquad 5\text{-}1$$

Where D_{ete} is end-to-end delay.

A node in the WSN can be modelled as a queening system as displayed in Figure 5-3. The notation from Kendall can be used to illustrate the model as A/S/c/K/D, in which the definition of every letter is[130]:

- A represents an inter-arrival time. Inter-arrival time also shows how often packets sent by the source to the destination. When traffic is dense, for instance, the packet inter-arrival is shorter than 5 seconds, and therefore, there will be more packets transmitted. In contrast, packets with inter-arrival time higher than 5 seconds mean that fewer packets are sent.
- S represents a service-time;
- C represents the number of servers;
- K represents the size of the buffer in bit or bytes;
- D represents a queue discipline.

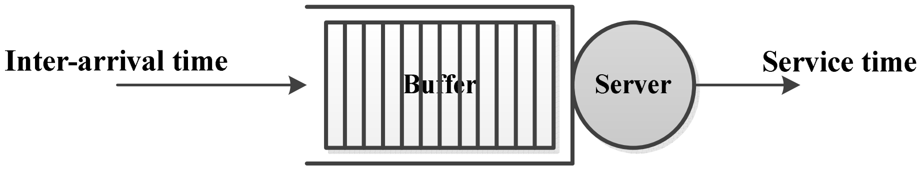

Figure 5-3. A sensor node model in WSN.

5.3.2 A Priority-Based Grid TDMA MAC

This section describes in-depth priority-based Time Division Multiple Access (TDMA) Medium Access Control (MAC). It still adopts the TDMA scheme, and the main idea of the proposed TDMA-MAC is to give priority to emergency traffic and reduce loss packets in the network, especially emergency traffic. To accomplish this goal, there are three steps introducing in this approach; a new TDMA format, arrangement of slots, and priority.

First, a new format of the frame is introduced in the proposed MAC. Since the approach considers the type of traffic generated by sensor nodes, the frame is classified into two types: a frame for emergency traffic T_e and a frame for emergency and monitoring traffic T_{em}. Sensor nodes which are generating emergency data perform T_e frame while those which are generating both emergency and monitoring data accomplishes T_{em} frame. Figure 5-4 presents two subsequently frames of the proposed MAC. In traditional MAC, all frames utilise the same format, and it does not consider emergency traffic. Here, the first frame is for emergency traffic while the second frame is for both emergency and monitoring traffic. The next frame has the same format as in these two frames. Therefore, the proposed MAC still accommodates to monitor interests by sending data traffic in every two consequents frames, and maintains emergency traffic in every frame. So, this approach can reduce the number of monitoring traffic but not emergency traffic. Moreover, since all traffic from sensor nodes are sent to the same destination, the BS, this approach controls the number of packets that are arriving in the BS or increases inter-arrival time. As a result, queuing delay in the buffer and packets loss is minimal.

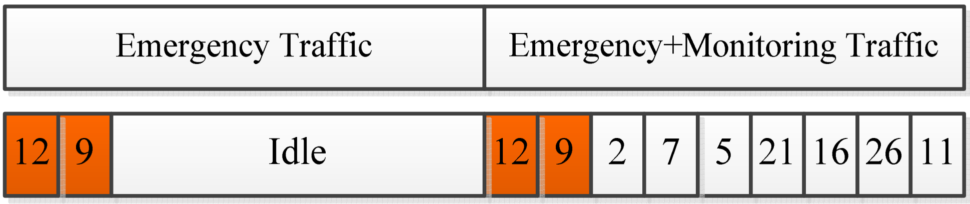

Figure 5-4. A new format of two consecutive TDMA frames.

The second step is to arrange the slot position of the frame according to the traffic characteristics. E-TDMA in LEACH does not consider the type of traffic sent by sensor nodes. Here, the first slot will be occupied by a first node joining to CH. Apparently, this position is based on the distance from a node to the CH. The close node to the CH is in the first slot, and so on. In the proposed MAC, the arrangement of slots is employed to prioritise emergency traffic. Figure 5-5 compares two frames: E-TDMA LEACH and the proposed MAC. A red slot in Figure 5-5 is a slot for emergency traffic while the white one is for monitoring traffic. Let's say that there are two nodes sending emergency traffic: node 12 and node 9. In E-TDMA LEACH, the slot's positions of emergency traffic can be anywhere in the frame as shown in Figure 5-5 (A). On the other hand, in the proposed MAC, slots for emergency traffic are at the commencement of the frame. Therefore, in Figure 5-5 (B), slots for node 12 and 9 are in the first and second positions. Hence, emergency traffic will be sent at the beginning of the frame, and as a result, they will arrive in the BS sooner than monitoring traffic.

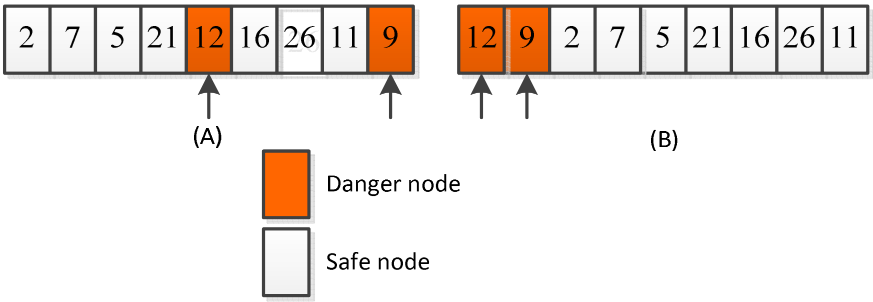

Figure 5-5. The arrangement of slots in the proposed MAC.

The last step is to give priority to emergency traffic by sending directly to the BS without aggregation in the CH. In the clustering network, the sensor node senses data periodically and sends to its CH. The CH performs aggregation for all data packets, and forwards these packets to the BS. A packet from the sensor node arrives at the CH must be put in the buffer, and wait for other packets from other nodes before they are delivered to the BS. So, the first packet that arrives in the CH has to wait for the last packet. Then, the CH aggregates these data. Hence, the first packet has the longest waiting time than others, while the last packet has the shortest one. When there are emergency data in these monitoring applications, such as fire detection, the system should deliver these data to the BS in minimum delay. Figure 5-6 shows two cases in data transmissions from the CM to the CH, and from the CH to the BS. In the traditional TDMA (Figure 5-6 (A)), data from the CH to the BS can be delivered if all data from the CM has been accepted in the BS without considering the status of nodes. Therefore, if there are emergency traffic from the dangerous nodes, these data should wait until all data have been collected in the CH. Nevertheless, in the proposed MAC (Figure 5-6 (B)), emergency traffic from the dangerous node can be sent directly to the BS since the CH can identify the traffic. As shown in Figure 5-6, traffic number 1 is emergency traffic, and there is no need to wait for aggregation because this traffic will send directly to the BS. Hence, processing delay in the CH is minimal, and end-to-end delay can be reduced as a whole.

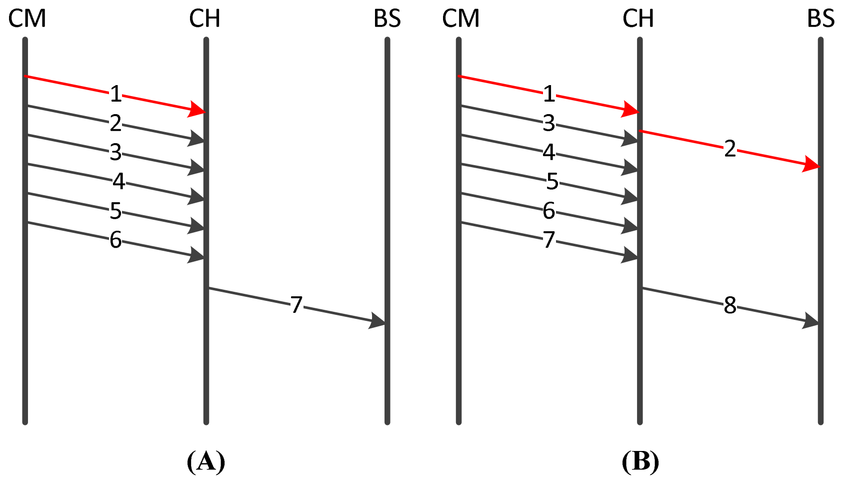

Figure 5-6. A timing diagram of sending data; (A) in the E-TDMA LEACH, (B) in the proposed MAC.

5.4 Performance Evaluation

As presented in chapter three and four, this section offers the parameters, scenarios, and performance metrics of the simulation. Due to the main concern in this chapter is to reduce delay of packets from emergency traffic, the key performance that is investigated is the average end-to-end delay and jitter. Mostly, all parameters of simulation and performance metrics in this section have the same values as in the previous chapter. On the other hand, in the scenarios of simulation, the number of sensor nodes and danger nodes are varied. The proposed approach is compared with LEACH and Grid, the clustering approach proposed in the chapter four.

5.4.1 Parameters of Simulation

Parameters of simulation applied in this chapter possess the same value as chapter three or four. As presented in chapter three, there are two types: radio and network parameters. Radio and network parameters in this section refer to Table 4-1 and Table 4-2 respectively.

5.4.2 Scenarios of Simulation

There are three scenarios of the simulation in this chapter.

- Run simulation for different total danger nodes (0, 2, 4, 6, 8, 10 danger nodes). The dangerous nodes are those that are close together. Overall average delay and delay for only packets from danger nodes are calculated. Moreover, PDR and FND are presented in the simulation results.
- Run simulation for different total nodes (100, 120, 140, 160, 180, 200 nodes). We test these conditions for one danger nodes and three danger nodes.

5.4.3 Performance Metrics

Since the main objective of the proposed approach is to deliver data to the BS in minimum delay, end-to-end packet delay and jitter are the critical performance metrics that want to be investigated. Below are overall metrics that are measured in this simulation:

- End-to-end delay: A time needed by a packet to travel from the source node to the destination node is referred to as end to end delay. Loss of packets in the network is not considered.
- Jitter: It is the average deviation of delays from the average delay.
- Energy consumed: It represents the sum of energy drained from all nodes in the network.
- Packet delivery ratio: The ratio of total packets collected by the BS to those sent by sources is called PDR.

5.5 Simulation Results and Discussion

This section provides all simulation results after testing the proposed approach with scenarios as in section 5.4.2. All results presented in the graph are average values with ten-time repetitions.

5.5.1 End-to-end Delay

A graph showing the average end-to-end delay in millisecond for different numbers of danger nodes is illustrated in Figure 5-7. In general, there is an increasing end-to-end delay as the number of burnt nodes goes up. End-to-end delay of the proposed approach is the lowest since there are a small number of packets sent to the BS; therefore, delay packets in the buffer is minimal. Nevertheless, when total danger nodes rise, total packets delivered to the BS increase because these danger nodes generate packets which are sent to the BS without aggregation in the CH. For instance, if there are two danger nodes, there will be six packets sent to the BS at the same time (two packets from danger nodes and four packets from the CH). Hence, increasing the number of danger nodes means increasing total packets in the buffer of the BS. On the other hand, because Grid and LEACH send data continuously, there are many packets queening in the buffer. The consequence, they experience higher end-to-end delay than the proposed approach. There is no effect in average end-to-end delay for both these approaches when the number of danger nodes changes since they do not consider the type of traffic in the network.

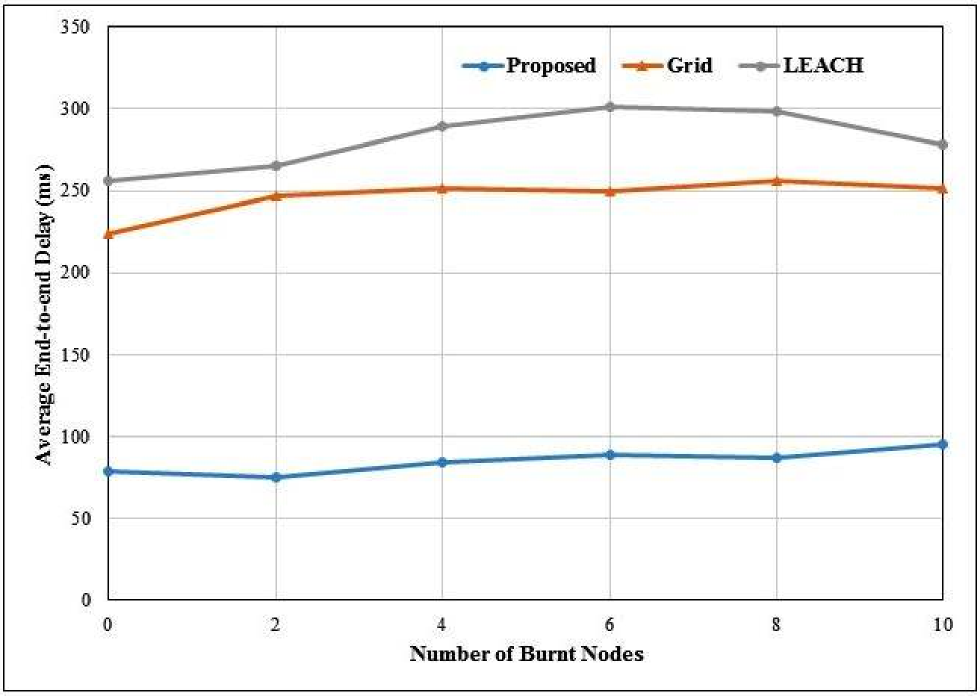

Figure 5-7. End-to-end delay vs different total danger nodes.

Figure 5-8 demonstrates the average end-to-end delay for emergency traffic versus different total danger nodes. Here, emergency traffic is packets generated by danger nodes. In the proposed approach, there is a small increase in average end-to-end delay when the number of danger nodes goes up. The reason for this is that as emergency traffic rises, there are many priority traffic in the buffer waiting to be processed by the BS. However, in LEACH and Grid, due to no priority mechanism, there are no significant effects on average end-to-end delay although total danger nodes vary until ten.

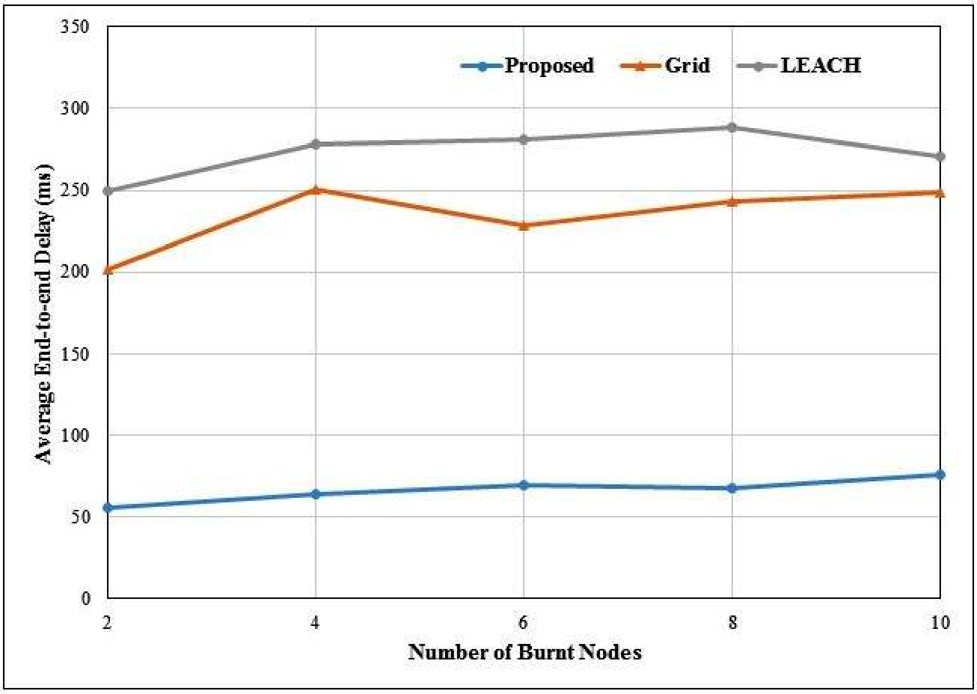

Figure 5-8. End-to-end delay for danger nodes only vs different total burnt nodes.

To study the effect of varying traffic on average end-to-end delay, the total number of nodes is varied from a hundred to two hundred. The result of this simulation is presented in Figure 5-9. As shown in the previous result, the proposed approach obtained the lowest end-to-end delay, which is around 80 millisecond when a total node in the network is a hundred. When there are two hundred nodes, end-to-end delay increases to 130 milliseconds, or the rising rate is around 63%. Grid and LEACH get an increasing rate of around 162% and 570% respectively. The total CH increases as the number of total nodes go up; therefore, many packets are delivered from the CH to the BS. This causes many packet queening in the BS and end-to-end delay increases. In LEACH, this effect and others, such as an unstable number of CHs and undistributed the positions of the CH, cause its delay gets worse.

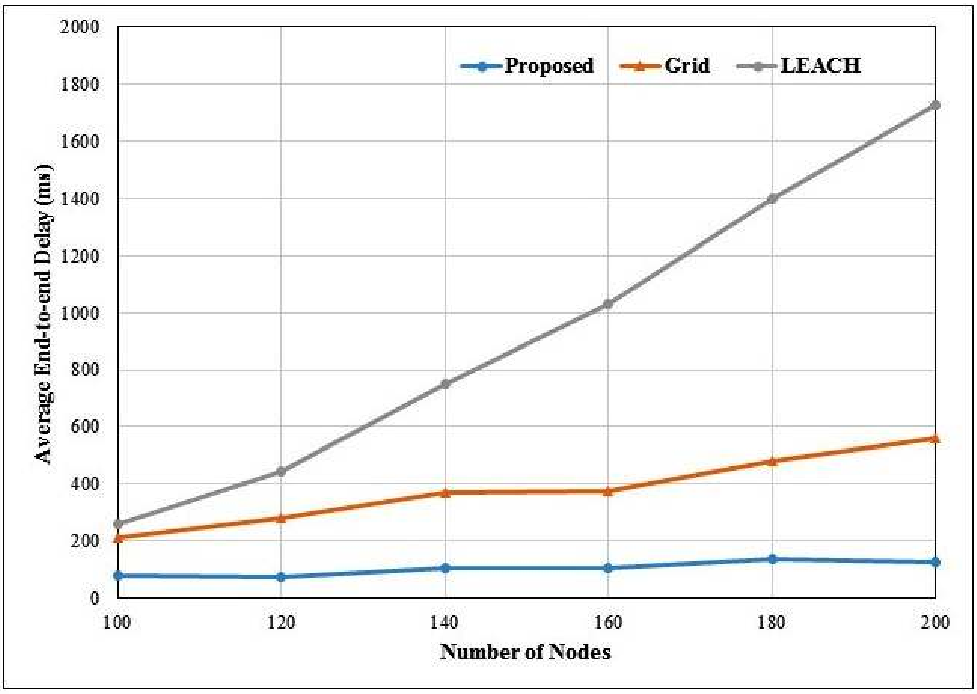

Figure 5-9. End-to-end delay vs different numbers of nodes with one danger node.

5.5.2 Jitter

Figure 5-10 plots jitter in millisecond for the proposed approach, Grid, and LEACH when total danger nodes are varied from two to ten. The danger status of the node is activated in the second round and dead in the next round. From the graph, the proposed approach acquires the lowest jitter, which is 8.4 millisecond without any burnt nodes. It can be seen that there is a slight rise in this metric as the number of danger node goes up. A possible explanation for this might be that when total danger nodes rise, total packets with low delay rise; as a result, the variation of delay enlarges. Owing to no priority method in Grid and LEACH, there is no different jitter as total burnt nodes go up.

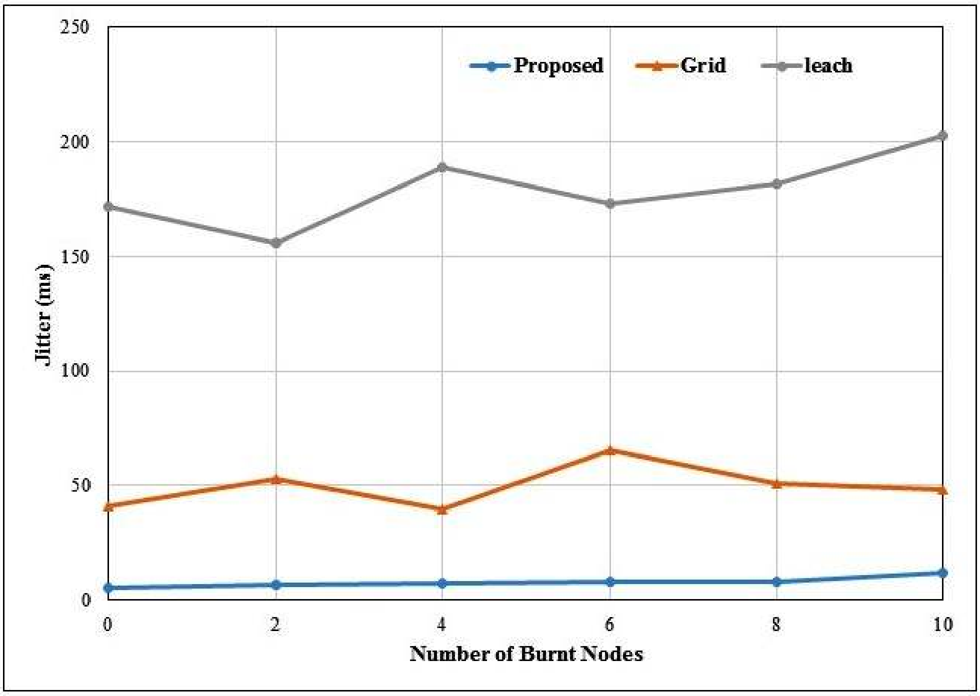

Figure 5-10. Jitter vs different total danger nodes.

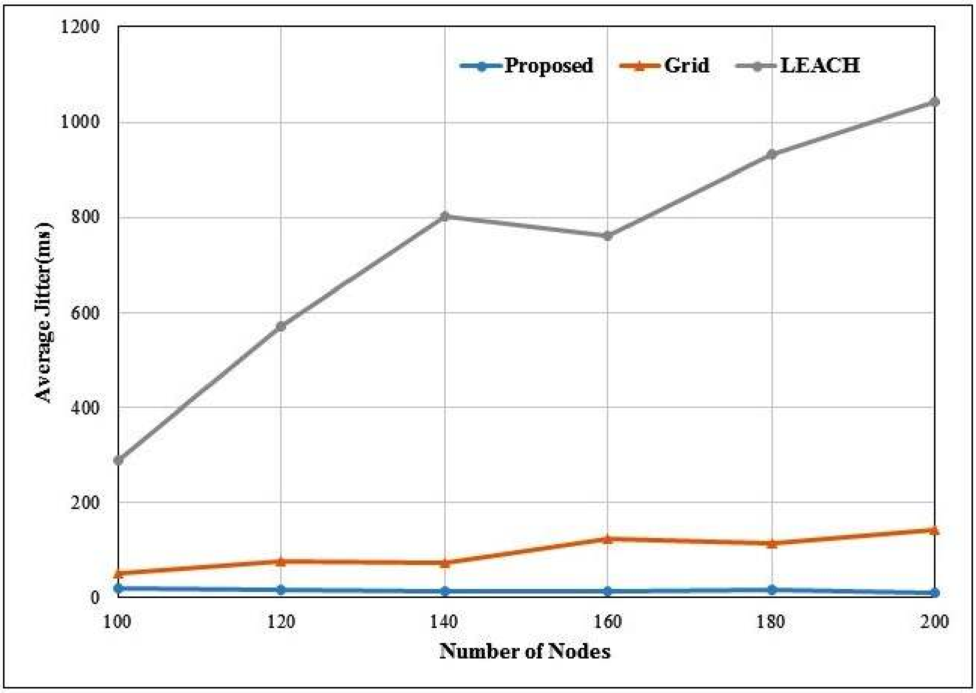

Figure 5-11. Jitter vs different numbers of nodes with one danger nodes.

To analyse the effect of increasing traffic to jitter in the network, different numbers of the sensor node is applied, and Figure 5-11 presents this result. Increasing nodes cause total CHs in the network raise, and there will be many packets sent to the BS. Since LEACH applies a threshold probability without considering the remaining energy of a node and its position in the network, there is a big dispersion on its end-to-end delay. This effect is significant as many packets delivered in the network. On the other hand, Grid and the proposed approach use the same method in choosing a CH, which is grid cluster based on remaining energy and distance, and as a result, their jitter is minimal. Moreover, due to the reduction in the number of packets sent, the proposed approach obtains the lowest jitter in these scenarios.

5.5.3 Energy Consumed

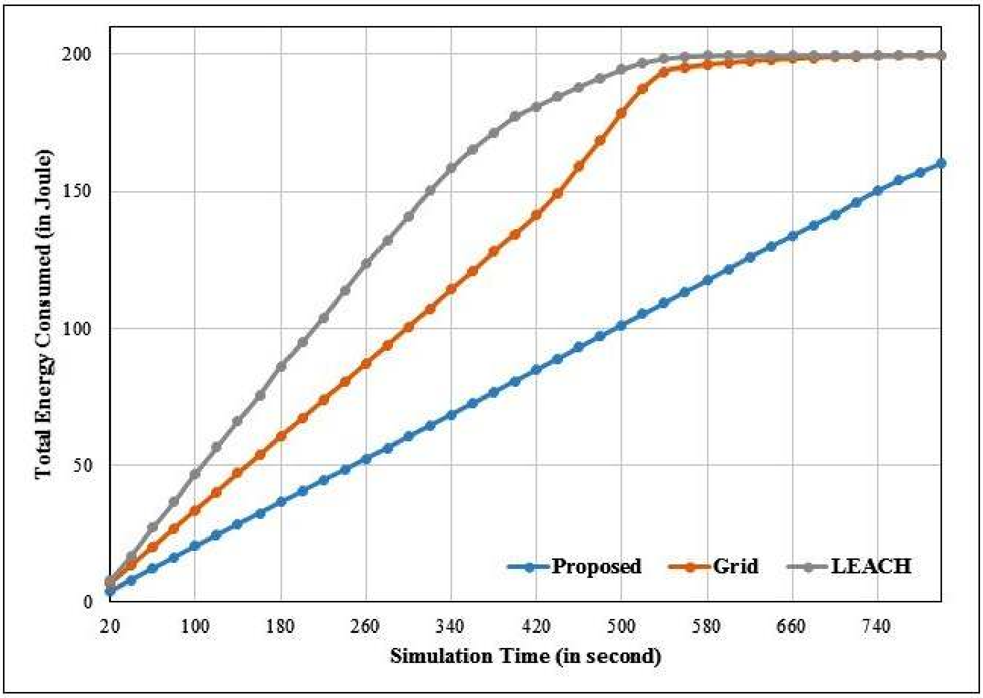

Figure 5-12. Energy consumed vs simulation time with 100 nodes and no burnt node.

Energy consumption for the proposed approach, Grid, and LEACH versus the simulation time is revealed in Figure 5-12. It is apparent from this figure that more energy expenditure as the simulation time increases. Due to the reduction in packets sent, the proposed approach acquires the lowest rate in energy consumption. After simulating for 800 seconds, the proposed approach consumed around 160 Joule in total or left energy of

40 Joule. In contrast, there is no energy left in LEACH and Grid since they spent almost 200 Joule of total their energy.

5.5.4 Packet Delivery Ratio (PDR)

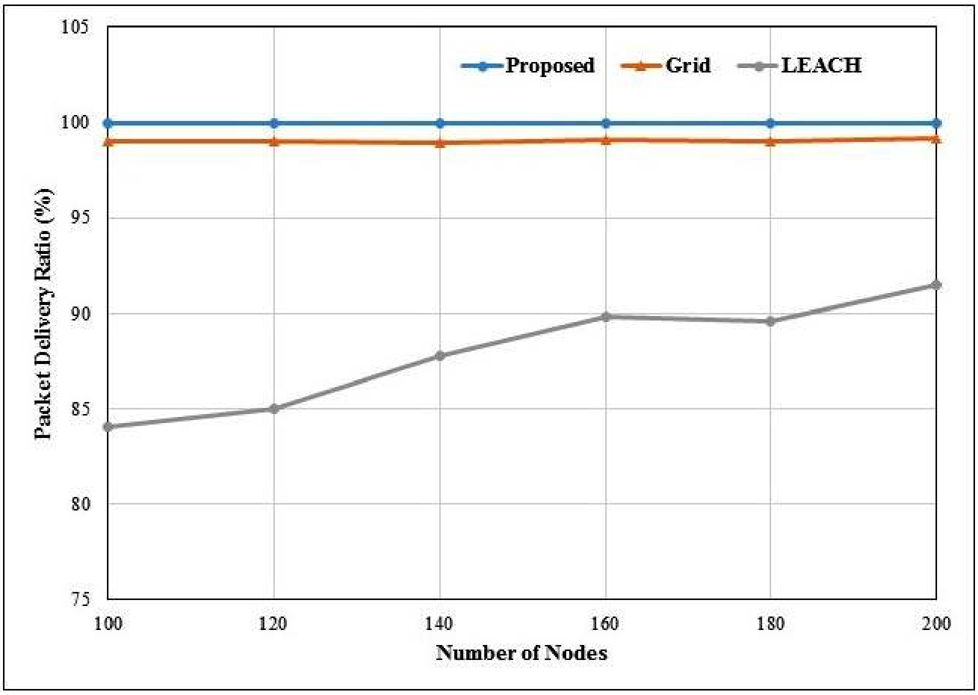

Figure 5-13. PDR vs different numbers of nodes with one danger node.

The result of the correlation between the packet delivery ratio and total sensor nodes is summarised in Figure 5-13. It can be seen from the graph that there is no significant change in PDR for the proposed approach and Grid when total sensor nodes change from a hundred to two hundred. The proposed approach and Grid gain 99.8% and 99.1% respectively. Both these methods utilise the same clustering approach, grid clustering, with constant total CHs and their member are distributed uniformly. Interestingly, PDR in LEACH was observed to rise slowly as total CHs go up owing to an increasing number of packets in the network.

5.5.5 Total Alive Nodes

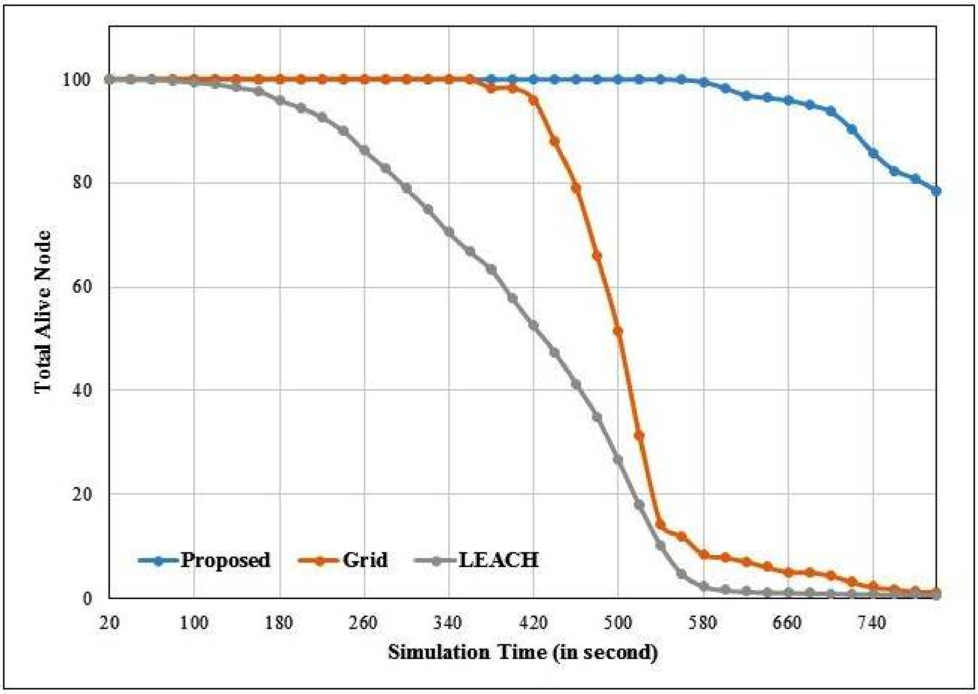

Figure 5-14. Total alive nodes vs the simulation time with 100 nodes and no burnt node.

A relationship between the total alive node and the simulation time is pointed out in Figure 5-14. This result is related to Figure 5-12, and it argues that controlling number of packets delivered to the network can influence network lifetime and energy consumed of sensor nodes. Here, the proposed approach reaches the longest lifetime, followed by Grid and LEACH.

5.5.6 Energy Efficiency

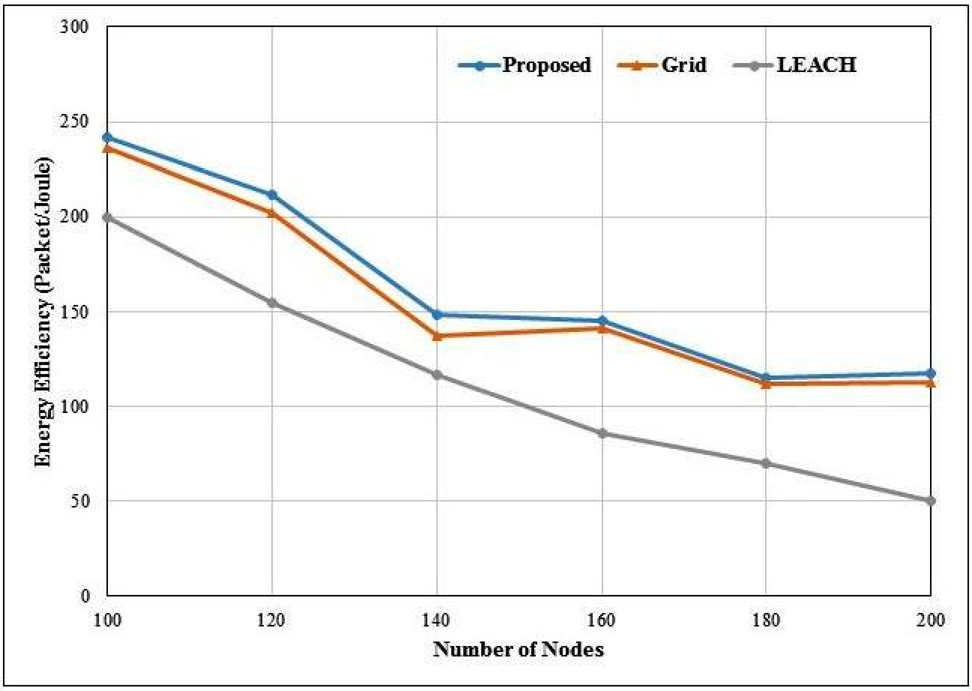

Figure 5-15. Energy efficiency vs different total nodes with one dead node.

To study how efficient energy consumption of sensor nodes, Figure 5-15 is presented. This metric is a comparison between total packets received in the BS and total energy consumption of sensor nodes in the network. Overall, the effectivity of energy consumption decreases as the number of nodes enlarges. The proposed approach and Grid almost obtain the same values for every number of total nodes due to the same method in performing clusters. Nevertheless, the proposed approach achieves better performance because its packet delivery ratio is higher than Grid. LEACH gets the lowest energy efficiency due to high loss packets.

5.6 Summary

This chapter mainly introduced a priority MAC based in TDMA for monitoring emergency applications of WSN. This scheme differs traffic generated by sensor nodes into emergency and non-emergency traffic. There is a priority algorithm for emergency traffic to reduce end-to-end delay. Moreover, it introduces a new TDMA frame format to control traffic in the network. Packets from emergency traffic are placed at the beginning of the transmission process, and they forward directly to the BS without aggregation in the CH. Simulation results show that there is a significant enhancement in terms of average end-to-end delay, jitter, energy consumed, packet delivery ratio, total alive node and energy efficiency. Overall average end-to-end delay of the proposed approach is the lowest, which is 78.79 millisecond, and if it is compared to Grid and LEACH, the improvement ratios are around 65% and 70%. Furthermore, end-to-end delay for emergency traffic decrease by about 25%. When total sensor nodes increase, there is a slight growth in end-to-end delay of the proposed approach and Grid. In contrast, LEACH experience a sharp rise. The proposed approach has the lowest jitter at only 5.34 seconds when no burnt nodes in the network while Grid and LEACH get approximately 40 seconds and 171 seconds. Since the proposed approach transmits packets nearly half of those in Grid, its rate of energy consumption is lower than Grid. Moreover, there is also an enhancement in total alive nodes. In connection with PDR, the proposed approach and Grid get the same trend. PDR for both these methods remains stable at around 99%, while in LEACH, surprisingly, its PDR raises gradually. The last metric observed is energy efficiency, and it has the same trend for all approaches. This metric decreases as total CHs go up, and the proposed approach gets the best value.

Chapter 6: Conclusions and Future Research Direction

6.1 Conclusions

WSN has been implemented in a broad range area; one of those is emergency applications. In these applications, when disaster situations such as fire or earthquake widen, sensor nodes near to this area can be disconnected or even destroy. These nodes cannot send data although they are emergency traffic. Furthermore, this emergency traffic should be delivered with minimum delay to reduce high impacts on the environment. To monitor disaster situations continuously, network lifetime of WSN needs to be increased. These characteristics result in a unique approach to enhance the performance of WSN. This thesis focuses on the development of routing and MAC protocol for emergency applications.

The path disconnection in routing packets due to disaster situations in monitoring emergency applications is the first issue tackled in this thesis, and it highlights in chapter three. Here, the node health status is introduced in order to differentiate the condition of the node, whether it is safe or danger. A safe node is a node which is far from the fire while when the node is close to the fire, it assigns a danger node. Health status is implemented in nodes with clustering topology since this topology offers low energy consumption for long life monitoring. In clustering topology, there are some Cluster Heads (CHs) forwarding data from Cluster Members (CMs) to the destination. A threshold probability from LEACH and the health status are parameters to choose the CH. Nodes in danger statuses are not allowed to be the CH. Moreover, multi-hop communication considering the distance between the CH to the destination is proposed to enhance network lifetime. The proposed approach is compared to LEACH and LEACH-C, and two scenarios are applied to all approaches; (1) nodes with no danger nodes, (2) nodes with one to five danger nodes. Results from the NS2 simulations have shown that the node health status and multi-hop communication have an impact on the performance of the network. Specifically, including the node health status in choosing the

CH can maintain data received, energy consumed, packet delivery ratio, and energy efficiency although total danger nodes grow. Also, there are enhancements in terms of data received, first node destroys, and half node destroys when multi-hop communication is utilised in the network. Data collected in the destination increased by 21% while first node destroys and half node destroys rise by 31% and 25% respectively.

To monitor emergency applications for a long period, nodes in WSN have to design with low energy consumption; one of approaches is clustering routing with optimal total CHs. In LEACH, total CHs vary over round, and therefore, its energy efficiency is not stable. A grid clustering with fixed total CHs is proposed in chapter four of this thesis. This approach divides the network into a fixed number of grids. The total grid is three until five per cent of the total number of nodes, which can result in high energy efficiency. In the first round, a node close to the centre of the grid has a higher probability of becoming a CH than others. On the other hand, in the second round onward, the CH is elected according to parameters such as remaining energy, the distance between the node and the centre of the grid, and the node health status. To study the performance of the proposed approach, NS2 is applied with two scenarios as in chapter three, with and without danger nodes. In general, applying fixed total CHs in an optimal value leads to a significant enhancement on WSN's performance. Simulation results indicated that first node destroys of the proposed approach is longer than LEACH and LEACH-C by 45% and 63% correspondingly, while in term of half node destroys, it increased by 18% and 9% compared to LEACH and LEACH-C. It is observed that the proposed approach rises energy efficiency by 17% over LEACH and 11% over LEACH-C. Results also discovered that the proposed approach delivers around 21% more data than LEACH. Furthermore, including the node health status as one of the parameters in choosing the CH results in the stabilisation of the WSN performance although there are some danger nodes in the area of monitoring.

The last issue concerning the implementation of WSN in monitoring emergency applications is how to deliver emergency traffic with minimum end-to-end delay, and it presented in chapter five. Emergency traffic is generated by a danger node when it is close to disaster events. Owing to the importance of this traffic, its priority should be higher than other traffic such as monitoring traffic. To overcome this issue, the proposed approach introduced three steps; a new TDMA frame, arrangement of slots, and priority. The format of two consecutive frames is one frame for only emergency traffic and another for emergency as well as monitoring traffic. Then, slots for emergency traffic are placed at the beginning of the frame. When these slots arrive in the CH, they are assigned as traffic with high priority and send directly to the BS without aggregation. The comparative study showed that the proposed approach has the lowest end-to-end delay. There are 65% improvement over the grid clustering and 70% improvement over LEACH in connection with overall end-to-end delay. End-to-end delay for emergency traffic decreases by 25% compared to overall end-to-end delay. In term of jitter, the approach has the lowest value, and the enhancements are around 87% and 92% compared to the grid clustering and LEACH. Moreover, the variation of total nodes and total burnt nodes only bring a little effect on end-to-end delay and jitter of the proposed approach. A new TDMA format in the proposed approach has small impacts on packet delivery ratio and energy efficiency, and it only brings a 1% improvement. On the other hand, it provides a big effect on network lifetime, in which it can extend alive nodes by 50% compared to the grid clustering.

6.2 Future Research Direction

The work done in this thesis mainly emphasises the enhancement of WSN performance for monitoring emergency applications such as forest fire or tsunami monitoring system. The proposed approaches offered are methods to improve routing and Medium Access Control (MAC), two important layers of WSN. NS2 is used to analyse the performance of the proposed approaches with some scenarios and parameters. Although the overall results have revealed that the proposed approaches increase the whole performance of WSN, there is still much work to be accomplished in the protocol design and implementation. Some of these are summarised as follow:

- An Energy Efficient Grid Clustering presented in chapter four has a constant number of CH. Every CH in the previous round choose CH for the current round based on its remaining energy and the distance. Unfortunately, when remaining energy of all nodes are low, nodes selected as CHs can destroy before the end of the round. As a result, at the beginning of the current round, the number of total CH reduces. This number will go down continuously until all nodes destroy. Therefore, it is recommended that further research is undertaken in modifying this grid clustering to overcome that issue.
- Although all proposed approaches in this thesis produce enhancements in WSN performance, these findings are limited by the use of NS2, a discrete event simulation tool. It would be interesting to develop a test bed in order to obtain realistic results.
- In general, emergency applications are applied in rural areas, where scalability and long-distance communication are their main characteristics. Nowadays, long distance communication such as LoRaWAN is a promising solution to increase the coverage of emergency applications. Further research regarding the implementation of the proposed approaches in LoRaWAN would be worthwhile.

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