DEVELOPMENT OF AN IMPROVED MULTI-HOP ROUTING PROTOCOL IN WIRELESS SENSOR NETWORKS BASED ON CLUSTER HEAD LOAD BALANCING TECHNIQUE

BY

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DECLARATION

I, Funom Samuel DADAH, hereby declare that the work in this dissertation titled "Development of an Improved Multi-Hop Routing Protocol in Wireless Sensor Networks based on Cluster Head Load Balancing Technique" has been carried out by me in the Department of Communications Engineering, Ahmadu Bello University Zaria. The information derived from literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

Funom Samuel DADAH (Student)	________________ Signature	________________ Date

CERTIFICATION

This Dissertation titled "**DEVELOPMENT OF AN IMPROVED MULTI-HOP ROUTING PROTOCOL IN WIRELESS SENSOR NETWORKS BASED ON CLUSTER HEAD LOAD BALANCING TECHNIQUE**" by Funom Samuel DADAH meets the regulations governing the award of Degree of Master of Science (MSc) in Telecommunications Engineering by the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Dr. A. D. Usman ________________ _____________
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DEDICATION

This research work is dedicated to The Almighty God, my entire family, and friends.

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ABSTRACT

Energy conservation in wireless sensor networks (WSNs) is a key area of research aimed at addressing the challenge of efficient energy utilization. This is due to the fact that the Sensor Nodes (SNs) have limited energy. The limited energy has to be utilized efficiently in order to provide longer network lifetime for the wireless sensor network (WSN). To reduce energy consumption in WSNs, an improved multi-hop routing protocol (mEEMRP) in WSNs based on cluster head (CH) load balancing technique was developed in this research work. The protocol used the residual energy (RE) of cluster heads (CHs) and adopted an election energy threshold (T_{nhCH}) to reduce the energy consumption of the SNs in the network, thereby increasing the network lifetime. This research work was carried out on MATLAB R2015b and the performance of the improved protocol was compared in terms of network lifetime (node death percentage), energy consumption percentage and number of packets received at the base station (BS) in a homogeneous WSN. Results obtained from simulation showed that mEEMRP achieved an average percentage improvement of the network lifetime, energy consumption percentage and number of packets received at the BS by 1.77%, 4.83%, and 7.41% respectively in a 200*m* by 200*m* network field. Also, results obtained from simulations showed that mEEMRP in a 400*m* by 400*m* network field improved the network lifetime, energy consumption percentage and number of packets received at the BS by 10.65%, 9.2%, and 12.5% respectively. Two network field scenarios were used to test the scalability of the improved protocol. The results of this research work showed that mEEMRP has a better network lifetime, better energy consumption and more number of packets received at the BS when compared with an existing energy efficient multi-hop routing protocol (EEMRP) in a WSN.

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LIST OF ABBREVIATIONS

BS	Base Station
CH	Cluster Head
CHs	Cluster Heads
CM	Communication Management node
EEMRP	Energy Efficient Multi-hop Routing Protocol
FND	First Node Death time
HNA	Half of Nodes Alive
LEACH	Low Energy Adaptive Clustering Hierarchy
LND	Last Node Death time
MAC	Media Access Control
mEEMRP	Improved EEMRP
NL	Network Lifetime
QoS	Quality of Service
RE	Residual Energy
RSS	Received Signal Strength
SN	Sensor Node
SNs	Sensor Nodes
TDMA	Time Division Multiple Access
WSN	Wireless Sensor Network
WSNs	Wireless Sensor Networks

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

A Wireless Sensor Network (WSN) is a network that is composed of hundreds of sensor devices that communicate over wireless channels (Vijayan & Raaza, 2016). This communication is governed by unique routing protocols (Vijayan & Raaza, 2016). The sensors are equipped with data processing and communicating capabilities with a sensing circuitry that is able to sense environmental conditions such as temperature, pressure, humidity levels etc, and convert them to electrical signals. These conditions help to tell certain details about the surrounding environment. The sensors transmit their sensed data via an inbuilt transmitter as electromagnetic signals to a designated base station (BS) either directly (Akkaya & Younis, 2005) or through an intermediate node (Gupta *et al.*, 2017).

Network lifetime is an important metric in WSNs. It is the maximum period of time that sensor nodes (SNs) are alive after they have been deployed in the field (Jan *et al.*, 2013). Network lifetime can also be defined in terms of first node death time, half of nodes alive and last node death (Wang *et al.*, 2012). It is necessary to have SNs alive for as long as possible. This is essential in order to avoid sensor holes in the network area.

WSNs are often deployed in areas or regions that are not easily accessible (Jan *et al.*, 2013). Batteries are therefore not easily replaced or recharged. This necessitates the need for energy conservation in the sensor nodes in order to maximize network lifetime and ensure that the network is not partitioned (Gupta *et al.*, 2017) so as to avoid sensor voids or holes (More & Raisinghani, 2016). To reduce the energy dissipation in the sensor network, clustering of SNs is one of the methods employed (Nayyar & Gupta, 2014). Clustering in WSN is employed as a technique to provide balance among SNs within the network so as to reduce energy consumption of individual SNs (Nayyar & Gupta, 2014). The clustering process involves selecting specific SNs to serve as cluster heads (CHs) while the rest of the SNs within the cluster serve as ordinary SNs. The CHs transfer aggregated data from ordinary SNs to the BS directly (Akkaya & Younis, 2005) or via multi-hop routes (Naranjo *et al.*, 2016).

With recent advances in micro-electromechanical-systems and wireless communication, WSN technologies provide a wide range of advantages over conventional networking technologies (Rawat *et al.*, 2014). Some of these advantages include lower cost, scalability, reliability, accuracy, flexibility and ease of deployment. Areas of application of WSNs include military, healthcare systems, and detecting wild fire in forest areas (Rawat *et al.*, 2014).

WSNs have several resource constraints which include, but are not limited to, limited amount of energy, limited storage capacity, short communication range, low bandwidth and limited processing capacity in each SN (Akkaya & Younis, 2005). These constraints lead to several challenges in the design and deployment of WSNs (Akkaya & Younis, 2005). These constraints must therefore be managed efficiently in order to maximize the lifetime of a WSN (Rawat *et al.*, 2014). The objective of research in WSN is to address these resource constraints by developing new concepts and protocols, improving upon existing protocols or developing hybrid protocols. Domains of research in WSN include media access control (MAC) protocols, routing techniques, congestion control, data collection, energy conservation, localization, security and applications (Rawat *et al.*, 2014). Among these challenges, energy serves as an important factor. To address this, researchers are therefore concerned with routing protocols and the energy efficiency factor (Kiani *et al.*, 2015).

This research also addressed the problem of energy conservation by adopting a CH load balancing technique that maintained load balance among CHs. The developed protocol increased the network lifetime. The protocol was implemented on MATLAB R2015a simulator. The results obtained are compared with the work of Huang *et al.,* (2017) based on node death percentage (network lifetime), energy consumption percentage and number of packets received at the BS.

1.2 Significance of Research

The significance and importance of this research work is that by developing an improved multi-hop routing protocol in WSNs based on CH load balancing, an improvement in energy consumption of SNs resulted in an increase in the network lifetime. This increase in network lifetime means that the possibility of having sensor holes in the network area has been greatly reduced, leading to an increase in the network performance.

1.3 Statement of Research Problem

Maximizing the limited energy of SNs is a major problem in WSNs. Protocols proposed in literature show that the problem of efficiently managing the energy of SNs in a WSN is as a result of inappropriate clustering schemes, inefficient CH selection algorithms and unbalanced load distribution in the network. The problem of unbalanced load distribution in the network can result in some SNs dying earlier than other SNs in the network. This results in sensor holes that limit the performance of the WSN. To further manage the limited energy of SNs in a WSN, this research work aimed at improving an existing multi-hop routing protocol by adopting a CH load balancing technique that considered residual energy (RE) of neighbor CHs to provide load balance among CHs in the network. This technique resulted in improved network lifetime, energy consumption percentage and number of packets received at the BS.

1.4 Aim and Objectives

The aim of this research work is to develop an improved multi-hop routing protocol in wireless sensor networks based on cluster head (CH) load balancing technique.

The objectives of the research work are as follows:

1. To replicate the Energy Efficient Multi-hop Routing Protocol (EEMRP) of Huang *et al.*, (2017).
2. To develop the improved multi-hop routing protocol based on CH load balancing technique (mEEMRP).
3. To compare the improved multi-hop routing protocol with the EEMRP protocol of Huang *et al.*, (2017) in terms of network lifetime (node death percentage), energy consumption percentage and number of packets received at the BS as performance metrics.

1.5 Scope of Research

This scope of this research work covers energy efficient routing protocols in WSNs that are aimed at utilizing the limited energy of SNs in order to increase network lifetime. This work is focused on the development of an improved multi-hop routing protocol based on CH load balancing technique with the view to improve network lifetime, energy consumption and the number of packets received at the BS.

1.6 Dissertation Organization

The organization of this dissertation is as follows: Chapter One presents the introduction; Chapter Two presents the literature review; Chapter Three presents the materials and methods used in the work; Chapter Four presents the results and discussion; Chapter Five presents the conclusion and recommendations for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter comprises the review of fundamental concepts in WSNs and similar prior reported works. These two reviews provide basic principles, model equations and protocols used in mitigating the problem of limited energy and other related problems. It also provides the level to which research has reached in this area. These reviews helped in the design of a different technique for the resolution of the problem of limited energy of SNs.

2.2 Review of Fundamental Concepts

In this section, the concepts that are fundamental to the research work are reviewed. This review examines relevant concepts, protocols and models. These fundamental concepts present the basis of WSN as it relates to the scope of this research work, thereby, giving a better understanding of the research work. These fundamental concepts are presented below.

2.2.1 Wireless Sensor Network (WSN)

A WSN is a network of tiny devices, called SNs, which are spatially distributed within a region or field and work cooperatively to communicate sensed data from the monitored field to a designated base station (BS) for further use by users (Rawat *et al.*, 2014). SNs communicate with each other via wireless strategies/links. These wireless strategies are governed by routing protocols. Routing protocols are responsible for discovering and maintaining energy efficient routes so as to make communication efficient and reliable (Singh & Sharma, 2015). A sensor node (SN) is made up of the following key components (Singh & Sharma, 2015): a microsensor, a microprocessor, a memory, a battery, and a transceiver to communicate with other nodes in the network (Singh & Sharma, 2015). The architecture of a SN is shown in Figure 2.1.

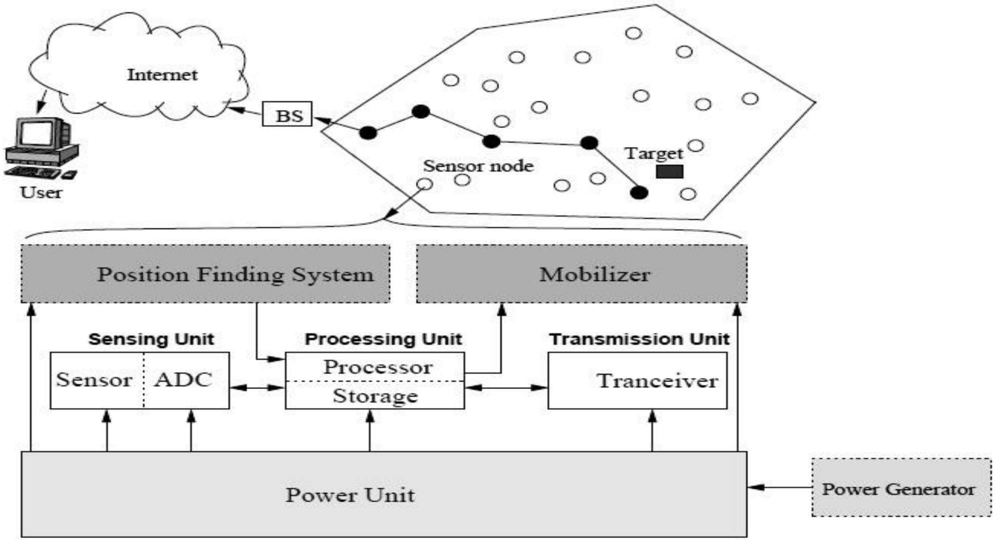

Figure 2.1: Sensor Node Architecture (Singh & Sharma, 2015)

2.2.2 WSN Routing Protocols

Routing protocols in WSNs are a set of rules that are responsible for discovering and maintaining energy efficient routes, in order to make communication reliable and efficient (Singh & Sharma, 2015). Routing protocols in WSNs differ from routing protocols in other networks in terms of infrastructure, reliability and energy constraint (Shenkutie & Shinde, 2011). These routing protocols can be classified into three classes (Sharma & Kaur, 2015):

1. Path establishment, which are further classified as proactive, reactive and hybrid.
2. Network structure, are further classified as flat or data centric, hierarchical based and location based.
3. Protocol operation, are further classified as multipath, query, bio-inspired, quality of service (QoS), coherent, non-coherent, mobility and negotiation based.

Figure 2.2 shows the different classes of routing protocols in WSNs and examples of each. For the purpose of this research work, routing protocols that are based on network structure are considered. The following sub-section provides more information on this routing protocol.

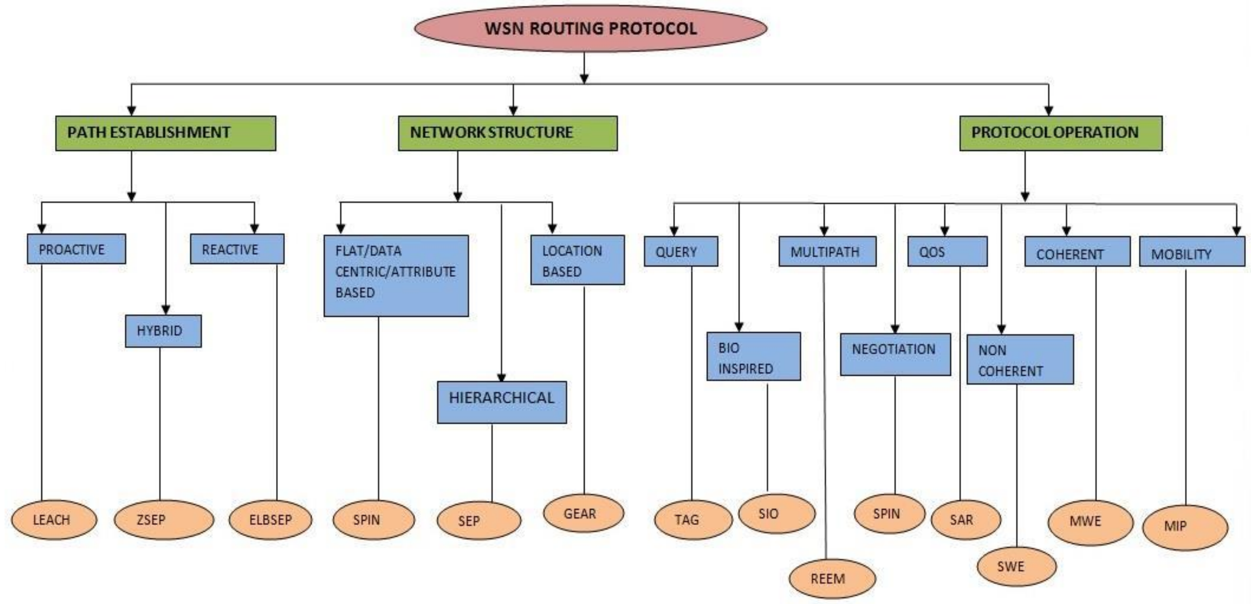

Figure 2.2: Classification of Routing Protocols in WSN (Sharma & Kaur, 2015)

2.2.2.1 Network Structure

Network structure based routing protocols are routing protocols that are designed on the basis of the functions of the SNs (Sharma & Kaur, 2015). These routing protocols are classified into three (Sharma & Kaur, 2015); flat or data centric based, hierarchical based and location based.

1. Flat or Data Centric Based – in flat based routing protocols, all the SNs perform the same function.
2. Hierarchical or Cluster Based – SNs in this routing protocol perform different functions. Hierarchical routing is based on clustering mechanism.

3. Location Based – in location based routing protocols, the location of SNs is used to route data to the BS.

Hierarchical or Cluster-based routing protocols are considered to be the most energy efficient routing protocols in WSNs (Jan *et al.*, 2013). Theses routing protocols employ clustering which is presented in the following sub-section.

2.2.3 Clustering in Wireless Sensor Networks

Clustering in WSN is employed as a technique to provide balance among SNs within the network so as to reduce energy consumption of individual SNs (Nayyar & Gupta, 2014). In clustering, a cluster is formed by grouping nodes within the sensor network into smaller groups having three types of nodes which include ordinary nodes, cluster heads and gateway nodes. The ordinary nodes are responsible for sensing specified parameters or conditions in the network region, the CHs are responsible for aggregating data from ordinary nodes and forwarding the data to the BS while gateway nodes are nodes that serve as intermediate nodes when a sending CH is too far from the designated BS. Advantages of clustering are (Nayyar & Gupta, 2014):

1. Reduction of the distance data travels when sent by ordinary nodes, thus saving significant amount of energy during data transmission.
2. Reduction of redundant data in CHs through data aggregation.

The clustering process takes place in two steps: CH selection and formation of clusters (Nayyar & Gupta, 2014). In the clustering process, specific nodes are selected to serve as CHs with the rest of the nodes within the cluster serving as ordinary nodes. The CHs transfer aggregated data from ordinary nodes to the BS directly (Akkaya & Younis, 2005) or via multi-hop communication (Naranjo *et al.*, 2016).

Cluster based hierarchical routing protocols are considered to be the most energy efficient routing protocols for WSNs (Jan *et al.*, 2013). An example of a cluster based hierarchical routing protocol is the Low Energy Adaptive Clustering Hierarchical (LEACH) based routing protocol which provides the foundation of clustering (Jan *et al.*, 2013). In LEACH, every SN randomly chooses a number between 0 and 1. If this number is less than a threshold value, that SN is elected as the CH for that round (Heinzelman *et al.*, 2000). The threshold value gives eligibility to SNs that can serve as CHs for each round and it is given as (Heinzelman *et al.*, 2000):

$$\mathrm{T(n)} = \begin{cases} \dfrac{\mathrm{P}}{1-\mathrm{P}*(\mathrm{r} \bmod (\frac{1}{\mathrm{P}}))} & \text{if n } \in \mathrm{G} \\ 0 & \text{otherwise} \end{cases} \tag{2.1}$$

where:

$\mathrm{T(n)}$ is the threshold

P is the desired percentage of CHs (e.g., P = 0.05)

r is the current round

G is the set of nodes that have not been CHs in the last 1/P rounds

Equation (2.1) is used in every round to determine SNs that can be elected as CHs. Nodes that are selected to serve as CHs for each round announce themselves as CHs by sending broadcast messages to the network. In the work of Huang *et al.*, (2017), functional nodes are selected to serve as communication management nodes and CHs according to a weight formula (Huang *et al.*, 2017) obtained as:

$$\mathrm{W_i^0} = \frac{\mathrm{E_i(t)} - \propto \times \mathrm{E_r(t)}av}{\propto \times \mathrm{E_r(t)}av} \times \frac{\mathrm{d_{av}}}{\mathrm{d}_{(s_i, s_0)}}, \qquad \text{if } \mathrm{E_i(t)} > \alpha \times \mathrm{E_r(t)_{av}} \tag{2.2}$$

where:

$E_i(t)$ is the residual energy of the i-th node

$E_r(t)_{av}$ is the average residual energy of the network in round r

α is the weighted coefficient of SNs, $0 < \alpha \leq 1$

$d(s_i,s_0)$ is the distance between SN i and the BS

d_{av} is the average distance between SNs and the BS

The CH selection algorithm sets an energy threshold ($\alpha \times E_r(t)$) for functional nodes. If the RE exceeds the energy threshold, SNs participate in the election (Huang *et al.*, 2017). Equation (2.2) gives eligibility to SNs that can participate in the election of functional nodes, with the SN having the highest weight being selected as CH for that round.

SNs then decide which cluster to join based on the Received Signal Strength (RSS) of the broadcasted messages by sending request messages to the corresponding CH (Liao & Zhu, 2013). The CH confirms SNs whose messages are received then adds them in its routing and allocates Time Division Multiple Access (TDMA) slots for the cluster members with each cluster member having its time slot to transmit data (Bsoul *et al.*, 2013). Figure 2.3 shows a representation of clusters in a WSN.

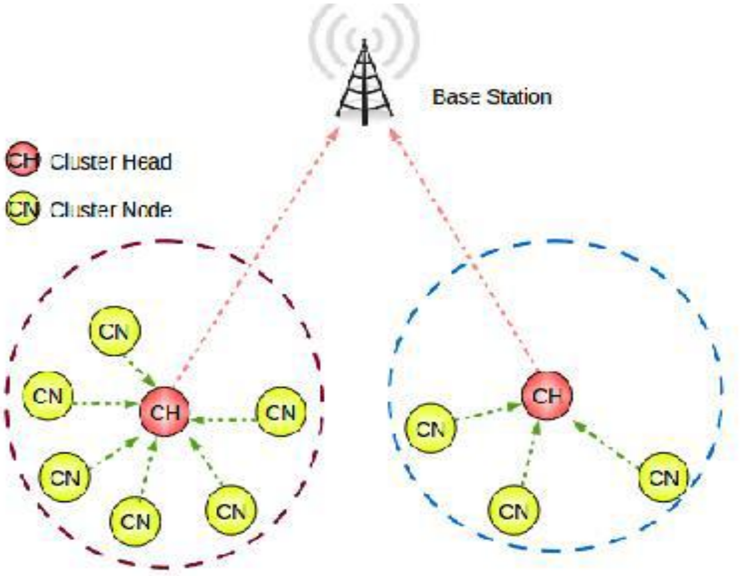

Figure 2.3: Clusters in a WSN (Gupta and Nayyar, 2014)

2.2.4 Multi-hop Routing in Wireless Sensor Networks

Multi-hop routing in WSN is routing of sensed data to a designated BS via multiple hops, as opposed to sending such data directly to the BS (Naranjo *et al.*, 2016). Multi-hop routing among CHs entails forwarding aggregated data from SNs to the BS via multiple CHs (Vijayan & Raaza, 2016) in every round. CHs close to the BS transmit data directly to the BS but where the distance between the CH and the BS is very large, more energy will be dissipated in transmitting the sensed data to the BS according to the radio energy model (Huang *et al.*, 2017). This results in depletion of more energy in the CHs. CHs can therefore form multi-hop routes whereby sensed data are transmitted to the BS (Huang *et al.*, 2017). By using multi-hop routes during the transmission of sensed data from the CHs to the BS, energy dissipation of CHs can be minimzed (Vijayan & Raaza, 2016). Therefore, when the distance between CHs and the BS is greater than the distance threshold (d_0), multi-hop routing between CHs is used in routing sensed data to the

BS so as to reduce energy dissipation of CHs (Huang *et al.*, 2017). In this research, d_0 was taken to be 87.7 m as specified in Huang *et al.*, (2017) based on equation (2.3) (Huang *et al.*, 2017):

$$d_0 = \sqrt{\frac{E_{\text{amp }1}}{E_{\text{amp }2}}} \tag{2.3}$$

where:

E_{amp1} is the amplifier transmitter dissipation if $d < d_0$ which is 10 pJ/bit/m^2

E_{amp2} is the amplifier transmitter dissipation if $d \geq d_0$ which is 0.0013 pJ/bit/m^2

d_0 was taken as 87.7 m by substituting the values of E_{amp1} and E_{amp2} into equation (2.3).

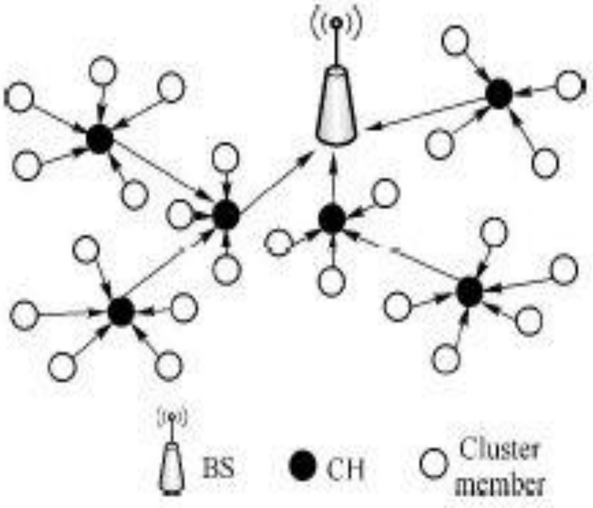

Figure 2.4: Network Topology formed by Multi-Hop Communication (Ke *et al.*, 2016)

2.2.5 Rounds in Cluster-based Hierarchical Routing Protocols

Cluster-based hierarchical routing protocols for WSNs operate in rounds (Jan *et al.*, 2013) or cycles (Vijayan & Raaza, 2016). Each round consists of a Setup phase and a Steady-State phase (Jan *et al.*, 2013). A round is the time interval from the beginning of the Setup phase to the end of the Steady-State phase (Vijayan & Raaza, 2016). A round is said to be complete when the BS finishes collecting all data (Vijayan & Raaza, 2016).

The Setup phase involves CH election and cluster formation. During the Steady-State phase, data flow is initiated from the CHs to the BS. CHs aggregate data from SNs in their respective clusters before forwarding the aggregated data to the BS (Jan *et al.*, 2013).

During a round, the transceiver can be transmitting, listening or sleeping (Shenkutie & Shinde, 2011). When transmitting, the transceiver is active and a SN forwards sensed data. When listening, the transceiver is active but the SN listens to the communication channel continuously to check for the arrival of any packets from a neighbor. During the sleeping state, all components of the SN are off so it can neither listen to its neighbor nor sense its environment (Shenkutie & Shinde, 2011). Transition between these states can be categorized into schedule based and event-based transitions (Shenkutie & Shinde, 2011). Therefore a SN in the sleep state will switch back to the sensing state after a certain period or when a predefined event occurs (Shenkutie & Shinde, 2011).

2.2.6 Radio Energy Model

Energy consumption in WSNs consists of two parts (Bsoul *et al.*, 2013): transmitting data and receiving data. The radio energy model used in WSN tells the amount of energy that a SN dissipates when transmitting or receiving data. The amount of energy a SN dissipates during the transmission of data, $E_{Tx}(k,d)$, is due to the transmitter circuitry $E_{Tx\text{-}elec}(k)$ and the transmitter amplifier $E_{Tx\text{-}amp}(k,d)$ as well as the distance between the transmitter and the receiver (Nikolidakis *et al.*, 2013).

The transmission energy of a k-bit message over a distance d is given by the radio energy model as (Naranjo *et al.*, 2016):

$$E_{Tx}(k, d) = E_{elec} . k + E_{amp} . k. d^{z} \tag{2.4}$$

where:

E_{elec} is the transmitter circuitry dissipation per bit

E_{amp} is the transmitter amplifier dissipation

k is the bit length

d is the distance of transmission between the transmitter and receiver.

z is the path loss exponent (with $2 \leq z \leq 4$)

From the radio channel model of equation (2.4), two channel models could be obtained to describe the transmission energy as (Naranjo *et al.*, 2016):

$$E_{Tx}(k, d) = \begin{cases} E_{elec} . k + E_{amp} . k. d^{2}, & \text{if } d < d_0 \\ E_{elec} . k + E_{amp} . k. d^{4}, & \text{if } d \geq d_0 \end{cases} \tag{2.5}$$

The amount of energy a sensor node dissipates when receiving data is given by (Bsoul *et al.*, 2013):

$$E_{Rx}(k) = E_{elec} \times k \tag{2.6}$$

where:

E_{elec} is the transmitter circuitry dissipation per bit

k is the bit length

The amount of energy dissipated when receiving data, as shown in equation (2.6), is constant for all SNs regardless of distance. Research is therefore focused more on minimizing the transmission energy of SNs.

Equation (2.5) gives the free space channel model (when, $d<d_0$) and multipath fading channel model (when, $d \geq d_0$) which are employed to calculate energy dissipated by SNs during data transmission. The protocol chooses channel model on the basis of distance between the transmitter and receiver (Ma *et al.*, 2016). Figure 2.5 shows the radio energy model as it applies to data transmission and reception in WSNs.

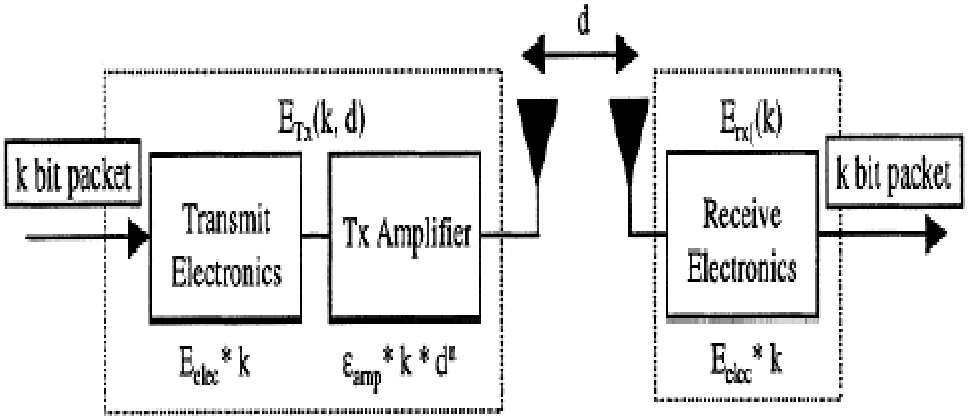

Figure 2.5: Radio Energy Dissipation Model (Ma *et al.*, 2016)

2.2.7 Cluster Head Load Balancing

Balancing load in WSNs is essential so as to ensure even distribution of energy levels throughout the network (Bsoul *et al.*, 2013). By balancing energy load throughout the network, energy consumption will be divided evenly between the SNs and the CHs (Bsoul *et al.*, 2013). This will result in SNs and CHs having residual energy levels that are close to each other, thereby, avoiding the situation where some SNs and CHs have high residual energy (RE) levels and others with RE levels close to zero (Bsoul *et al.*, 2013). This is important in WSNs as it gives rise to an improved average residual energy value which in turn leads to an extension of the network lifetime (Bsoul *et al.*, 2013). In this work, CH load balancing was used so as to improve the energy consumption percentage of the network thereby extending the network lifetime.

2.2.8 Threshold

Some routing protocols in WSNs make use of thresholds as presented in the work of Manjeshwar and Agrawal, (2002). Thresholds are used in WSNs to specify a value above which a predefined response to an event occurs (Manjeshwar & Agrawal, 2001). The threshold is a parameter that consists of hard threshold (H_T) and soft threshold (S_T) as used in the work of Manjeshwar & Agrawal, (2002). H_T refers to a particular value of an attribute beyond which a SN can be triggered to start transmitting (Manjeshwar & Agrawal, 2001). S_T is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit (Manjeshwar & Agrawal, 2001). To meet the unique requirements of WSNs and ensure even distribution of energy load among CHs, this research work used an election energy threshold (T_{nhCH}). It was used to select the CH with sufficient residual energy as next hop during the multi-hop routing of aggregated data from CH to BS. For this research work, T_{nhCH} was taken to be the average residual energy of neighbor CHs in that round.

2.2.9 Performance Metrics

Several performance metrics are employed in WSNs. Some of the performance metrics include:

1. Network lifetime (Wang *et al.*, 2012)
2. Number of packets (Wang *et al.*, 2012)
3. Energy consumption percentage (Huang *et al.*, 2017)

For the purpose of this research work, network lifetime, energy consumption percentage and number of packets received at the BS were used as performance metrics. These metrics were used to evaluate the performance of the developed protocol and for validating with the work of Huang *et al.*, (2017).

2.2.9.1 Network Lifetime

Network lifetime can be defined as the maximum period of time that SNs are alive after they have been deployed in the field (Jan *et al.*, 2013). The network lifetime can also be defined using different metrics, which include: First Node Death (FND), Half of the Nodes Alive (HNA) and Last Node Death (LND) (Wang *et al.*, 2012). From the work of Huang *et al.*, (2017), the theoritical network lifetime can be given as:

$$C = \frac{E_o}{R} \tag{2.7}$$

where:

C is the average energy consumption

E_0 is the total intial energy

R is the theoritical network lifetime

First Node Death: This metric refers to the estimated time it takes for the first node in a WSN to use up all of its energy and die (Handy *et al.*, 2002). This can also be used as a basis for estimating the network lifetime of a WSN. In the work of Bsoul *et al.*, (2013), FND is the time it takes for the battery of the first SN to be completely depleted.

Half of the Nodes Alive: The HNA metric is the time that it takes for exactly half of the total number of SNs in the network to use up their battery (Handy *et al.*, 2002).

Last Node Death: LND refers to the estimated time it takes for the last node in a WSN to use up all of its energy and die (Handy *et al.,* 2002).

2.2.9.2 Average Residual Energy

The average residual energy is the sum of residual energies of SNs in a sensor network divided by the total number of SNs in the network (Bsoul *et al.*, 2013). The average residual energy is defined mathematically (Huang *et al.,* 2017) as:

$$E_r(t)_{av} = \frac{E_r(t)}{N} \tag{2.8}$$

where:

$E_r(t)$ is the total residual energy of the whole network at round r and time t

N is the number of SNs in the network

r is the number of rounds the network has run

From equation (2.8), the total RE of all SNs is computed at the end of each round and divided by the total number of SNs still alive (Bsoul *et al.*, 2013).

2.2.9.3 Energy Consumption Percentage

The amount of energy a SN consumes mainly includes the the energy consumed during data transmission, reception and aggregation. The total amount of energy consumed in a network therefore refers to the total amount of energy that is dissipated during all these processes in every round (Huang *et al*., 2017). Energy consumption percentage is therefore the percentage of the total initial energy of the network that has been used as the network lifetime increases.

2.2.9.4 Number of Packets

This metric refers to the number of information carrying packets that are successfully received at the BS at the expense of a specific amount of energy (Wang *et al*., 2012).

2.2.10 Performance Evaluation

The performance of the improved multi-hop protocol (mEEMRP) is compared with the work of Huang *et al*, (2017) in terms of network lifetime (node death percentage), energy consumption percentage, and number of packets received at the BS as performance metrics. These performance metrics are explained in section (2.2.9). Simulations were carried out using MATLAB R2015b. The following equations were used for the performance evaluation of mEEMRP:

a. Percentage improvement of the network lifetime is given as:

$$\%\ \text{NL Improvement} = \frac{\text{NL}_{\text{mEEMRP}} - \text{NL}_{\text{EEMRP}}}{\text{NL}_{\text{EEMRP}}} \tag{2.9}$$

where:

% NL Improvement is the percentage improvement of the network lifetime of mEEMRP

$\text{NL}_{\text{mEEMRP}}$ is the network lifetime of mEEMRP

NL_{EEMRP} is the network lifetime of EEMRP

b. Average percentage improvement of the energy consumption percentage is given as:

$$\%\ \text{Average Improvement (E)} = \frac{\text{NR}_{\text{avmEEMRP}} - \text{NR}_{\text{avEEMRP}}}{\text{NR}_{\text{avmEEMRP}}} \tag{2.10}$$

where:

% Average Improvement (E) is the average percentage improvement of mEEMRP

$NR_{avmEEMRP}$ is the average number of rounds in mEEMRP

$NR_{avEEMRP}$ is the average number of rounds in EEMRP

c. Average percentage improvement of the number of packets received at the BS is given as:

$$\% \text{ Average improvement (NP)} = \frac{NP_{avmEEMRP} - NP_{avEEMRP}}{NP_{avEEMRP}} \quad (2.11)$$

where:

% Average improvement (NP) is the average percentage improvement for number of packets for mEEMRP

$NP_{avmEEMRP}$ is the average number of packets in mEEMRP

$NP_{avEEMRP}$ is the average number of packets in EEMRP

2.2.11 Flowchart of EEMRP

The existing CH election flowchart and the existing multi-hop routing flowchart for the work of Huang *et al.*, (2017) are presented in Figures 2.6 and 2.7 respectively. The flowchart of the improved multi-hop routing protocol (mEEMRP) is presented in Chapter Three.

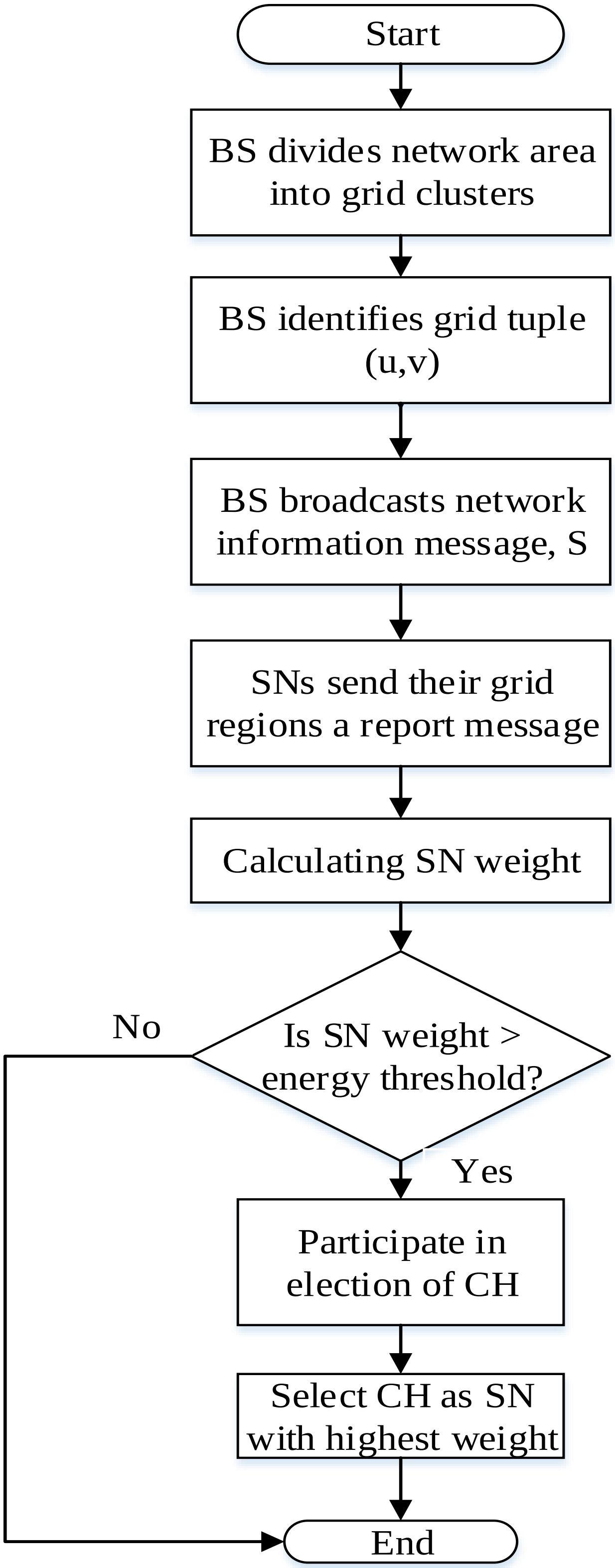

Figure 2.6: Existing CH Election Flowchart (Huang *et al.*, 2017)

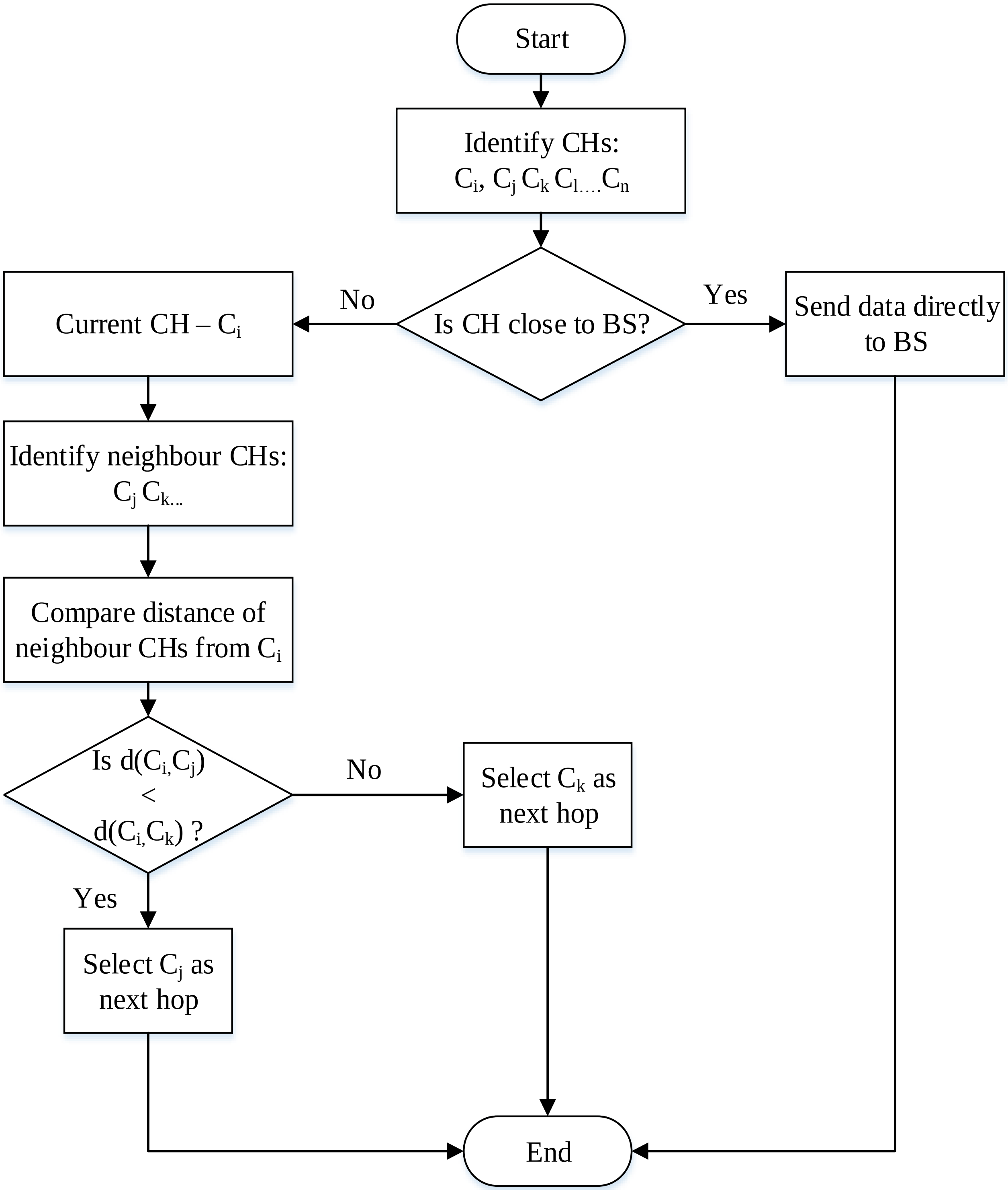

Figure 2.7: Existing Multi-hop Routing Flowchart (EEMRP) (Huang *et al.*, 2017)

2.3 Review of Similar Works

Some literatures that are relevant to the research area of energy conservation and multi-hop routing in wireless sensor network are discussed in this section. The section explains different techniques and protocols that were proposed and implemented by other researchers to deal with the problem of limited energy of SNs in WSNs. This review provides improvements and limitations in various proposed techniques.

Wang *et al., (*2012) proposed a WSN clustering algorithm based on energy information and CHs expectation called Low Energy Adaptive Clustering Hierarchy with Sliding Window and Dynamic number of Nodes (LEACH-SWDN). The adoption of a sliding window in this work caused a dynamic change in the upper limit of the interval that generated random numbers. The interval was no longer fixed at (0,1), but changed dynamically with the running of the network to $(0,E_{average\_nch}/E_{i\_max})$. Dynamic optimization of the number of CHs ensured a gradual reduction in the number of CHs with the reduction in the number of living nodes so that the number of CHs could be maintained in the optimal range. Simulation results showed an improvement in the network lifetime and uniformity of energy consumption in the network cycle over Low Energy Adaptive Clustering Hierarchy (LEACH) and LEACH with deterministic CH selection. Also, this protocol maintained the number of CHs at an optimal range even when the number of SNs in the network began to reduce. The problem with this work is that there was the possibility of CHs being concentrated in one area of the network as the protocol did not give priority to the distance between CHs. This would have led to uneven distribution of energy load in the network which in turn might have led to sensor voids as a result of nodes in one part of the network dying early.

Bsoul *et al., (*2013) proposed an energy efficient threshold-based clustering protocol (a modified LEACH) for WSNs which provided a new way of creating distributed clusters. In the work, a threshold was calculated and set by the BS after considering SN residual energy and the distance between SNs. This threshold was used to select CHs from the SNs in the network. The sensor node with the highest threshold was selected as the first CH. Other CHs were selected after considering the minimum distance between every CH and the next (MDBECHN) in order to ensure CHs were evenly distributed and not concentrated in one place. If the BS could not meet the MDBECHN, it reduced the value. Simulation results showed that their protocol outperforms LEACH in two scenarios; constant number of SNs with varied number of CHs and varied number of SNs and constant percentage of CHs, by increasing the time till the first node dies and by reducing the average residual energy. However, due to the increased number of messages and communication involved in the protocol, a lot of communication overhead is required to ensure it runs properly. This increased communication caused by the transmission of control messages depletes the SNs of valuable energy.

Mahmood *et al.*, (2013) proposed a modified LEACH (MODLEACH) by introducing an efficient CH replacement scheme and dual transmitting power levels. In the proposed protocol, a threshold was used in determining whether a CH could serve as CH for the next round or had to be replaced. A CH would only be replaced when its energy level fell below a certain threshold, thereby minimizing the overhead of the protocol, which in turn reduced the energy that would have been expended in selecting new CHs and creating new clusters. Furthermore, the protocol utilized dual transmitting power levels to amplify transmitted signals according to the nature of the transmission; intra cluster transmission, inter cluster transmission and CH to BS transmission. Finally, hard and soft thresholds were implemented on MODLEACH to give comparison on the performance of the protocol. The proposed protocol was evaluated using CH formation, throughput and network lifetime as performance metrics and MODLEACH showed significant improvements in all performance metrics. However, by extending the number of rounds a node could serve as CH, this could result in such a node dying quickly because it has to use its energy to a certain level before it stops serving as CH. This scenario gives rise to uneven distribution of energy throughout the network as some nodes will have higher residual energy levels compared to other nodes that are serving as CH.

Nikolidakis *et al.*, (2013) proposed a routing protocol to ensure energy conservation through balanced clustering called Equalized Cluster Head Election Routing Protocol (ECHERP). In their protocol, the network was modeled as a linear system where Gaussian Elimination algorithm calculated the combinations of nodes that could be chosen as CHs in order to extend the network lifetime. For CH selection, current and estimated future residual energy of a node were considered, as well as the number of rounds that the node could serve as CH so as to maximize lifetime. Results showed that this protocol outperformed previously proposed protocols like LEACH, Power Efficient Gathering of Sensor Information Systems (PEGASIS) and Base-station Controlled Dynamic Clustering Protocol (BCDCP) in terms of number of nodes alive per round and last node death (LND) time. However, the increased computational complexity of the protocol, arising from increased overhead, can result in SNs depleting more energy when providing the BS with information. This in turn can result in reducing the network lifetime in terms of FND.

Javaid *et al.*, (2014) proposed an application aware and heterogeneity aware routing protocol in WSNs called Application-aware Threshold-based Centralized Energy Efficient Clustering (ATCEEC). This protocol proposed a network model that contained three types of nodes which were capable of sensing two environmental conditions; temperature and humidity. Also, the network was divided into three regions; Low Energy Region (LER), Medium Energy Region

(MER) and High Energy Region (HER). In the proposed protocol, the BS used an advanced centrally controlled algorithm which considered four parameters for selection of CHs. These were: initial energy of nodes, residual energy of nodes, average energy of the network and location of nodes. ATCEEC operated in rounds with each round divided into Network Settling Phase (NSP) and Network Transmission Phase (NTP). During NSP, CHs were selected and clusters were formed. In NTP, specific application parameters were sensed based on specified thresholds (idle threshold, temperature threshold, humidity threshold and critical threshold) and the data were transmitted to the BS. Results from simulation showed ATCEEC performed better than LEACH, Stable Election-based routing Protocol (SEP), Enhanced-SEP and Distributed Energy Efficient Clustering (DEEC) protocol in terms of stability period, network lifetime, instability period, number of CHs and the number of packets delivered to the BS. However, by grouping nodes with the same energy levels in the same region, a situation may arise where sensor holes could be created especially in the LER, due to the uneven distribution of energy levels within the network.

Guiloufi *et al.*, (2014) proposed an energy efficient clustering algorithm (EECA) for fixed and mobile SNs by considering three scenarios; fixed nodes (EECA-F), constant mobility nodes (EECA-M1) and dynamic mobility nodes (EECA-M2). In all three scenarios, the respective protocols considered node degree, consumed energy of node and distance of the node from the BS. These parameters were used in calculating weights for every SN. In EECA-M1, three ranges of speed were defined; 1 (0-5km/h), 2 (5-20km/h) and 3 (20-44km/h). The speed of a SN belonged to one of these groups and was therefore considered constant. For EECA-M2, node mobility (Mob(u)) was also used in determining the weights for the SNs. The node with the least weight, which represented the node with maximum degree, minimum consumed energy and closest to the BS, was elected as the CH. Results showed improvement in energy saving of sensor nodes by reducing the power consumption of nodes. However, this protocol leads to increased overhead as a result of the different scenarios in which it operates. This increased complexity will further lead to considerable loss of energy which will lead to nodes dying quicker.

Gwavava & Ramanaiah, (2015) proposed Yet Another LEACH (YA-LEACH), a WSN routing protocol that used centralized cluster formation to ensure optimal clusters and allow CHs to extend operation into multiple rounds to achieve energy savings. The protocol used an alternative (vice) CH that took over the role of CH when the residual energy of the CH was not enough to last the entire round. The centralized clustering scheme ensured fair distribution of CHs throughout the network. A CH was allowed to extend its role into another round provided it had enough residual energy. This residual energy was calculated as the minimum energy required before the CH has to transfer its role to the vice-CH. By so doing, the proposed protocol saved considerable amounts of setup cost as clustering did not have to be done after every round. Simulation results showed an increase in terms of network lifetime and data throughput. However, by extending the number of rounds a CH remained as CH, there could be uneven distribution of energy throughout the network as CHs have to use up almost all of their energy before relinquishing their roles as CHs. This could also lead to such nodes dying quicker and resulting in sensor holes in the network.

Gaba *et al.*, (2015) proposed a Hybrid Energy Efficient Clustering Algorithm (HEECA), a combination of Energy Efficient Congestion Avoidance (EECA-F) in wireless multimedia sensor networks and Hierarchical-Power Efficient GAthering in Sensor Information Systems (H-PEGASIS). The proposed protocol used a centralized clustering algorithm where EECA-F calculated weights for each SN in the network. These weights were calculated based on the parameters: consumed energy of a node and the distance of the node to the BS. The node with the least weight, which was also the node with maximum degree, was selected as the CH. Aggregated data from CHs were routed to the BS via multi-hop routes, as governed by H-PEGASIS. The results that were obtained from simulation showed an increase in energy saving in SNs, thus, making the network lifetime longer. However, the authors failed to address the problem of uneven distribution of CHs as some CHs may have more cluster members compared to others thereby leading to uneven energy load among the CHs.

Vijayan & Raaza, (2016) proposed a novel cluster arrangement energy efficient routing protocol (CAERP). The authors proposed an efficient way of node clustering which involved uneven clustering of SNs, with clusters close to the BS having fewer cluster members compared to clusters farther away. This clustering scheme was achieved with the help of a calculated competition range, R. CHs were selected considering the nodes with the minimum distance from the BS as well as residual energy levels. An efficient multi-hop routing algorithm was used to route aggregated data to the BS by picking next hops based on minimum distance. Simulation results showed an improvement in network lifetime and average residual energy per round. However, by considering minimum distance between CHs when routing data to the BS, CHs with higher residual energy could be neglected as next hops leading to uneven energy levels among CHs in the network. This could further lead to reduced network lifetime in terms of first node death (FND) time.

Ke *et al.*, (2016) proposed a novel energy aware hierarchical cluster-based (NEAHC) routing protocol to minimize total energy consumption and ensure fairness of energy consumption between nodes. In the proposed protocol, CHs were selected on the basis of remaining energy.

Nodes with low energy levels switch between sleep and active modes in order to balance energy consumption. Relay node choosing problem was modeled as a nonlinear programming problem and the property of convex function was used to find the optimal solution. Simulation results showed there was significant improvement in terms of network lifetime, energy consumption per round and reliable delivery of data. However, the proposed protocol does not ensure even distribution of CHs throughout the network as CHs were chosen based on remaining energy alone. This can lead to uneven energy distribution in the WSN since CHs were not efficiently distributed throughout the network.

Singh & Verma, (2017) proposed an energy efficient cross layer based adaptive threshold routing protocol for WSNs. The proposed protocol was proposed for networks which are heterogeneous and was based on adaptive threshold sensitive distributed energy efficient cross layer routing protocol. The principle of weights was used in selecting CHs; a ratio of the average energy of the entire network and the residual energy of the SN. The protocol also incorporated reactive and proactive network concepts. Simulation results showed that the proposed protocol outperforms other protocols in the area of data packets received at the BS, network residual energy and the number of nodes alive. However, the proposed protocol does not lead to optimal distribution of CHs in the network since SNs with high residual energy could be located in one part of the network. This will mean more CHs will be selected from that part of the network causing other SNs to do more work in transmitting data to their CHs. This will result in uneven distribution of energy load in the network.

Huang *et al.*, (2017) proposed an energy efficient multi-hop routing protocol (EEMRP) based on grid clustering to tackle the problem of unbalanced energy consumption of SNs. In the protocol, the network area was divided into unequal grids which formed different levels of clusters. In order to minimize the energy consumption of nodes, the protocol optimized the process of electing functional nodes by combining nodes' energy level, location and levels of the network. A SN that had a higher RE and was located closer to the BS in each grid had a higher probability to become a functional node. A shortest path multi-hop routing algorithm was adopted in routing aggregated data to the BS. Simulation results showed an extension in network lifetime and better performance of energy balance and efficiency in larger network areas when compared to other routing protocols. However, with increase in rounds and disparity in energy levels in the network, multi-hop routing on the basis of distance alone could lead to CHs with higher RE levels being neglected as next hops. This can further lead to uneven energy levels and unbalanced energy consumption among CHs in the network which can result in reduction in network lifetime in terms of FND.

Han *et al.*, (2017) proposed a distributed energy-efficient clustering (DCE) protocol for heterogeneous WSNs based on double-phase CH election. In the proposed protocol, CH election was in two stages. In the first stage, tentative CHs were selected based on probabilities that were decided by the relative levels of initial and residual energy of SNs. In the second stage, the proposed protocol decided the final set of CHs by replacing the low-energy tentative CHs with SNs that had higher energy levels in the cluster. These two stages guaranteed that nodes with more energy had a higher probability of becoming CHs. Aggregated data from each CH was forwarded to the BS via single-hop routes. Simulation results showed that the proposed DCE protocol performs better than other protocols in terms of stability period. However, by adopting two stages when selecting CHs, more communication was involved which results in increased overhead and increased transmissions which lead to energy loss. Also by adopting single-hop transmission of aggregated data from CHs to the BS, more energy will be dissipated by CHs that are located far away from the BS compared to CHs that were located closer to the BS. This will lead to uneven energy levels in the CHs in every round.

From the literatures reviewed, the challenge of limited energy in WSNs remains a major issue that needs to be addressed. The problem of distributing energy load among SNs has also not been adequately addressed. Works addressing the challenge of limited energy and even distribution of energy load in the network have not sufficiently considered distribution of energy load among CHs during multi-hop routing of data to the BS. Most works considered reducing transmission distance so as to reduce energy dissipated during transmission which did not address load balance of the network. This research work is an improvement of the work of Huang *et al.*, (2017) that proposed an energy efficient multi-hop routing protocol. The improved protocol efficiently utilizes the limited energy of SNs by considering residual energy levels of CHs during the multi-hop routing of aggregated data to the BS for longer lifetime of nodes.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter the detailed procedures and methods adopted in realizing this research work is presented. The steps of the methodology adopted for this research, in order to develop the improved multi-hop routing for WSNs based on CH load balancing technique are presented in section (3.3).

3.2 Materials

The materials that were used in carrying out this research work include: MATLAB R2015b, a WSN, sensor nodes and the EEMRP routing protocol. The WSN and the sensor nodes were simulated on the MATLAB simulator.

3.3 Methodology

The step by step approach of the methodology is itemized as follows:

1. Replication of the Energy Efficient Multi-hop Routing Protocol (EEMRP) of Huang *et al.*, (2017) by carrying out the following steps:
   a) Dividing the network area into equal rectangular lanes (parallel to the y-axis) with each lane having several grids (parallel to the x-axis).
   b) Identifying each grid by a tuple (u,v), representing the vth grid of the uth lane.
   c) Broadcasting of network information message, S, to all SNs by the BS.

      S {W, n, A, H}

      where:

      W is width of lane
      n is the number of lanes
      A is used to store the grids' number of the network
      H indicates the length of the grid

   d) SNs sending their grid regions a report message

R_s (i, (u,v), $E_i(t)$, level (i), (x,y), $W_i^0(t)$)

where:

(x,y) is the location coordinates of SNs

i is the SNs' ID

(u,v) is a grid to which the SN belongs

$E_i(t)$ is the residual energy of the i-th node

level (i) indicates the level at which the node is located

W_i^0 is a weight used in selecting functional nodes

e) Electing functional nodes in different grid clusters by selecting SN with RE that exceeds energy threshold.
f) Estimating multi-hop routing path by:
    i. Identifying neighboring CHs; with C_i as current CH and C_j and C_k as neighboring CHs.
    ii. Comparing distance from C_j to C_i and C_k to C_i.
    iii. Selecting next hop as CH with minimum distance from C_i.
g) Routing of data to BS along estimated multi-hop path.

2. Development of the improved multi-hop routing protocol (mEEMRP) using the following steps:
    a) Repeating steps 1a – 1e.
    b) Estimating next hop by setting election energy threshold (T_{nhCH}) and checking distances of neighboring CHs to C_i.
    c) Selecting next hop as the CH with RE above threshold set in 2b and with a distance $\leq d_0$.
    d) Routing of data to BS along estimated multi-hop path.
3. Comparison of the improved multi-hop routing protocol with the EEMRP technique of Huang *et al.*, (2017) using network lifetime (node death percentage), energy consumption percentage and number of packets received at the BS as performance metrics.

3.4 Replication of the Energy Efficient Multi-hop Routing Protocol (EEMRP)

Figure 2.7 shows the flowchart for the implementation of the existing Energy Efficient Multi-hop Routing Protocol in WSNs. The processes involved in the replication of the EEMRP are discussed in the following sub-sections:

3.4.1 Dividing the network area into grids

At first, 400 nodes are deployed randomly in a 200 m^2 field (for the first scenario) and a 400 m^2 field (for the second scenario). These network areas are divided into grids according to the following two steps:

i. The network area is divided into n equal rectangular lanes that are parallel to the y-axis. The width of each lane is denoted as W and the length of each lane is denoted M. the rectangular lanes are numbered from 1 to n starting from the left to the right.

ii. Each lane is divided into several grids with each grid parallel to the x-axis. The number of grids in each lane is dependent on the distance of the lane from the BS and the location of the rectangular lane. Grids located farther away from the BS have longer length and greater region. Each grid is assigned different levels.

Figure 3.1 shows a representation of the division of the network area of a WSN into grids with their respective levels. The developed MATLAB code for the network division is shown in Appendix A.

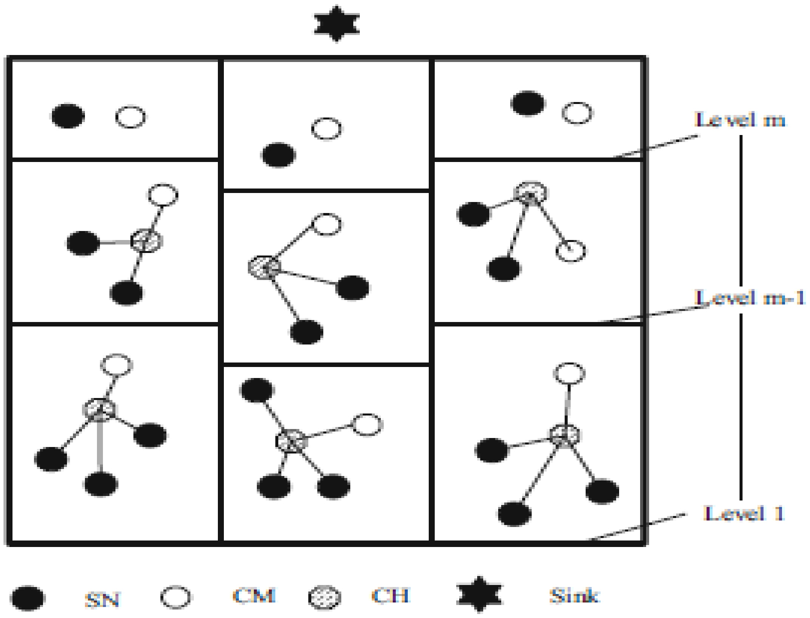

Figure 3.1: Network Area Division into Grids (Huang *et al.*, 2017)

3.4.2 Identifying each Grid

Grids in this research work are used in place of conventional clusters in WSN. The ID of each grid is identified by a tuple (u,v). This tuple represents the *v*th grid of the *u*th lane. The boundary of grid (u,v) is defined as follows (Huang *et al.*, 2017):

$$\begin{cases} (p-1) \times W < u \leq p \times W; \\ \sum_{k=0}^{q-1} h_{pk} < v \leq \sum_{k=0}^{q} h_{pk}; \; p = 1,2,\ldots,n; q = 1,\ldots,m \end{cases} \tag{3.1}$$

where:

$h_{10} = h_{20} = \ldots = h_{n0} = 0$

h_{pk} is the height of the grid in column p and line k

The algorithm used in calculating the *i*th node's level and grid is as follows:

Input: Coordinates (x,y) of node i and boundary equations;

Output: Grids ID and determined level;

Step 1: Calculate the horizontal direction: $u = {}^{x}/_{w}$;

Step 2: Calculate the vertical direction through the loop: $v = \sum_{k=0}^{i} h_{uk}$

Step 3: Define Grid's ID (u,v) and Level (i) = v

3.4.3 Broadcasting Network Information Message

During initialization of the network, the BS broadcasts a network information message to all SNs. The network information message, S {W, n, A, H}, comprises of the following parameters:

i. W is the lane width

ii. n is the number of lanes

iii. A = $\{a_1, a_2, \ldots, a_n\}$, which is used to store the grids' number of the network and a_i indicates the level and the number of rectangular lane i.

iv. $H = \{H_1, H_2, \ldots, H_n\}$ Array H_i indicates the length of grid.

where $H_p = \{h_{p1}, h_{p2}, \ldots, h_{pq}\}$, $p = 1, 2, \ldots, n$; $q = 1, 2, \ldots, n$.

And $\sum_{k=1}^{q} h_{pk} = M = n \times W$ (3.2)

where:

n is the number of lanes

W is the width of the lanes

3.4.4 Sensor Nodes Send Report Message

After network initialization, the protocol executes election of functional nodes. These functional nodes include CHs and Communication Management (CM) nodes. For this election purpose, certain network parameters are required. Sensor nodes (SNs) therefore broadcast report messages to their grid regions to enable the election of functional nodes. Before the first round, SNs send their grid regions a report message:

R_s (i, (u,v), E_i(t), level (i), (x,y), W_i^0(t))

where:

(x,y) is the location coordinates of SNs

i is the SNs' ID

(u,v) is a grid to which the SN belongs

$E_i(t)$ is the residual energy of the i-th node

level (i) indicates the level at which the node is located

W_i^0 is a weight used in selecting functional nodes

In order to conserve energy, SNs only send data to other SNs within the grid region with a specific power. This enables SNs to collect the state information of all the SNs in the WSN in order to do pretreatment for election of functional nodes. The developed MATLAB code for broadcasting grid region report message is shown in Appendix B.

3.4.5 Electing Functional Nodes

During the election of functional nodes, each SN uses the information from its neighbor within its grid. Each SN compares its residual energy with a set threshold. SNs with residual energy levels higher than the set threshold participate in the election of functional nodes. Equation (2.2) is used to determine the SN with higher probability to become a functional node. This weight formula considers two factors: residual energy of SNs and distance of the SN from the BS. Under the condition that the residual energy of a SN exceeds the set threshold, the SN with higher residual energy and located closest to the BS has a higher probability to become a functional node. The developed MATLAB code for electing functional nodes is shown in Appendix C.

3.4.6 Estimating Multi-Hop Routing Path

After clustering and sensing of data, CHs aggregate the sensed data and forward them to a designated BS. As network size increases and the distance between CHs and the BS increases, multi-hop routing is adopted in order to reduce the amount of energy dissipated during the transmission of data. The multi-hop routing path is established by comparing distances between neighboring CHs and selecting paths with shortest distance. From the sending CH to the BS, intermediate CHs are searched step by step to establish a routing table based on shortest distance.

3.2.6.1 Calculating distance between sensor nodes

The distance, $d(s_i,s_j)$, between two SNs s_i and s_j is calculated using the Cartesian coordinates of the SNs and is given as (Huang *et al.,*2017):

$$d(s_i,s_j) = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \qquad (3.3)$$

where:

x_i and y_i are the Cartesian coordinates of SN s_i

x_j and y_j are the Cartesian coordinates of SN s_j

Equation (3.3) is used in determining the distances between CHs. Paths with the shortest distance leading to the BS are selected as the multi-hop route. The developed MATLAB code for determining the distance between SNs is as shown:

```
function dij = dist(nodeI, nodeJ)
```

```
        dij = sqrt(((nodeI(1)-nodeJ(1))^2) + ((nodeI(2)-nodeJ(2))^2));
    end
```

3.4.7 Routing Data to Base Station

A sending CH searches for all its neighboring CHs. It selects the nearest CH after comparing the distances between each neighbor CH and itself according to equation (3.3). The sending CH then adds the nearest neighbor CH to its routing table. This process is repeated for other sending CHs until data are transferred to the BS. The MATLAB code for the multi-hop routing of data to the BS is shown in Appendix D.

3.5 Development of The Improved Multi-Hop Routing Protocol (mEEMRP)

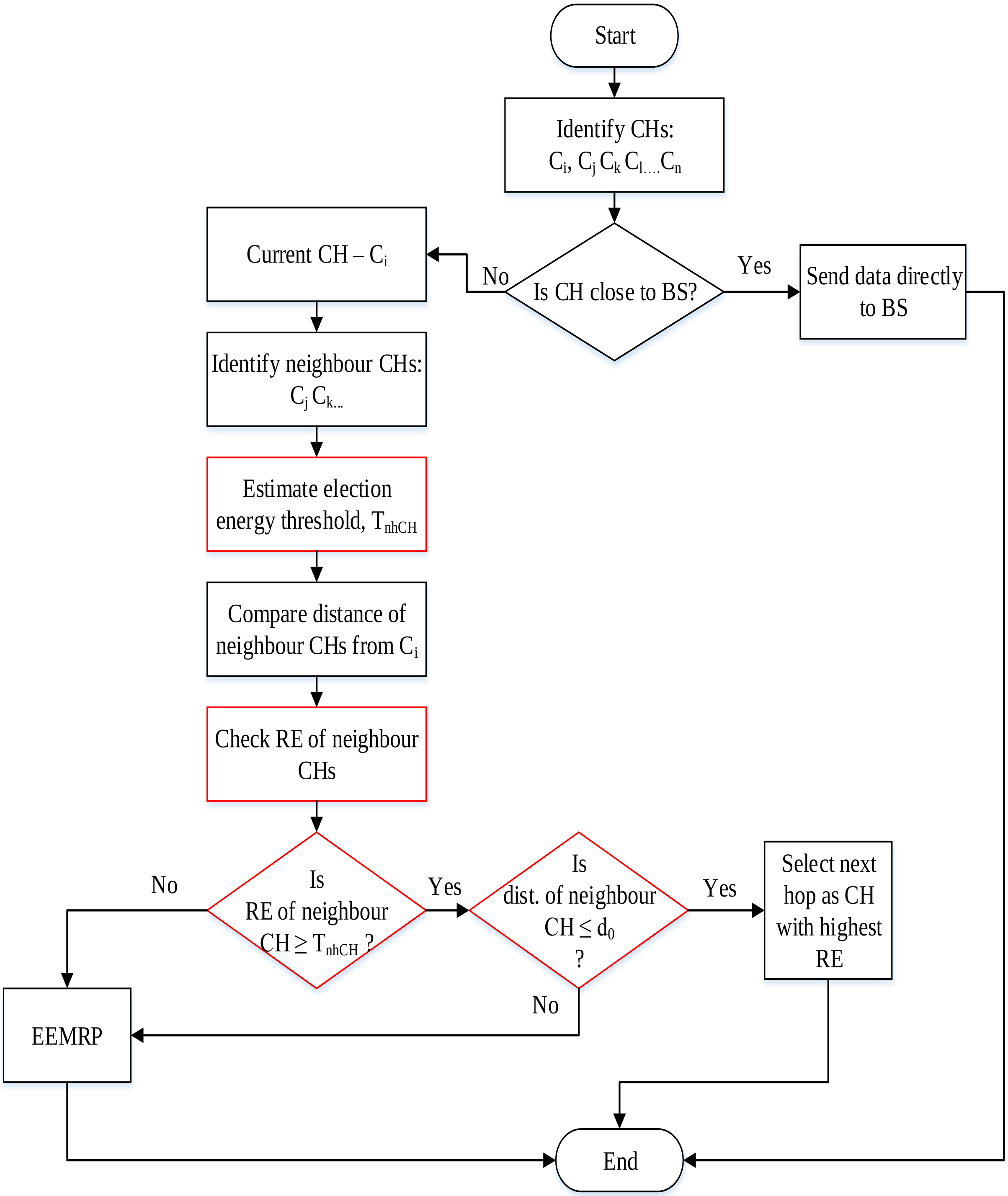

Figure 3.2: Flowchart of the Improved Multi-hop Routing Protocol (mEEMRP)

Figure 3.2 presents the flowchart of the improved protocol. The red highlights indicate the modifications made to the EEMRP of Huang *et al.*, (2017). These modifications incorporate consideration of energy levels of CHs as well as the distance between CHs during the multi-hop routing of data to the BS unlike in EEMRP where only distance was considered. The energy levels of CHs were used in calculating the election energy threshold presented in section (3.5.1). This threshold was used in determining the CHs that were eligible to serve as next-hop CHs during the multi-hop routing of data to the BS. The distance between CHs with RE levels above the threshold were then checked to see if it lied within the distance threshold.

For the development of the improved multi-hop routing protocol based on CH load balancing technique, steps 1a – 1e of the methodology in section (3.3) were repeated. In this improved protocol, during the multi-hop routing of aggregated data, next hops are selected based on an election energy threshold, T_{nhCH}. CHs that satisfy this threshold requirement and are located within a distance threshold (d_0) are selected as next hops so as to ensure that energy levels of CHs are evenly distributed throughout the network. The election energy threshold is explained as follows:

3.5.1 Election Energy Threshold

During the network initialization, all SNs send their residual energy and locations to the BS. By so doing, the BS has information on the state of all SNs within the network region. After the Set-up phase, when CHs begin to forward data towards the BS, the BS uses the information that the SNs had previously provided it in identifying neighboring CHs to every CH. Once neighbor CHs have been identified, the election energy threshold is set by calculating the average residual energy of the neighbor CHs.

$$T_{nhCH} = \frac{\sum_{n=1}^{m} \mathrm{RE}\ (\mathrm{neighbour\ \ CHs})}{m} \tag{3.4}$$

where:

T_{nhCH} is the election energy threshold

RE (neighbor CHs) is the residual energy of neighbor CHs

m is the number of neighbor CHs

The threshold value obtained from equation (3.4), along with the distances calculated using equation (3.3) of the neighboring CHs is used in determining the next hop in the establishment of the multi-hop route. This process is adopted for every transmitting CH. In this approach, aggregated data from each CH is forwarded to another CH after considering the residual energy levels of neighboring CHs as well as their distances

3.5.2 Multi-Hop Routing to the Base Station

In the improved multi-hop routing protocol (mEEMRP), data is forwarded to the designated BS along the path established after considering the RE levels of neighbor CHs and their distances. The RE levels give basis for setting the election energy threshold. The distances are considered so that a transmitting CH does not use too much energy when transmitting, taking into account the radio energy model in equation (2.4). The MATLAB code for the multi-hop routing of mEEMRP is shown in Appendix E.

3.6 Determining Network Lifetime, Energy Consumption Percentage and Number of Packets Received at the Base Station

As specified in section 3.8, starting with an initial energy of 0.5 Joules, for every data transmitted and received, energy is consumed by SNs. The amount of energy consumed during data transmission by a SN is given by equation (2.4) and the amount of energy consumed by a SN when receiving data is given by equation (2.6). This consumed energy is subtracted from the initial energy of the SN depending on the number of times data has been transmitted and received by the SN. This process continues until every SN has used up its energy. The network lifetime is the time it takes for a SN to use up all of its energy.

As network lifetime increases, SNs use more of their energy until the energy becomes zero at which point a SN is dead. The time it takes for all SNs in the network to die is referred to as the network lifetime. After every round of data transmission and reception, the average residual energy of the network is obtained using equation (2.7). The rate at which SNs deplete their energy is used in determining the energy consumption percentage as specified in section (2.2.9.3).

3.7 Scalabity Test

For the scalability test, two network areas were considered; $200m\ by\ 200m$ and $400m\ by\ 400m$, according to the work of Huang *et al.*, (2017). In both network scenarios, the network lifetime is considered as the time it takes for all SNs to use up their energy.

3.8 Experimental Specifications

All assumptions and parameters considered during simulation are presented thus:

a. The location of the BS and all sensor nodes are fixed.

b. The deployment of sensor nodes was random.

c. The number of SNs deployed is 400.

d. The location of the BS (100,200) is known in advance in the $200m\ by\ 200m$ sensor field.

e. The location of the BS (200,400) is known in advance in the $400m\ by\ 400m$ sensor field.

f. Rectangle numbers in the $200m\ by\ 200m$ sensor field is 4.

g. Rectangle numbers in the $400m\ by\ 400m$ sensor field is 8.

h. Rectangle width for both network scenarios is $50m$

i. The data packet size is 800 bits.

j. Initial energy of SNs is 0.5 J.

k. Grid numbers of each rectangle in the $200m\ by\ 200m$ is: A = 4,4,4,4

l. Grid numbers of each rectangle in the $400m\ by\ 400m$ is: A = 5,6,7,7,7,7,6,5

m. E_{amp1} is 10 pJ/bit/m^2

n. E_{amp2} is 0.0013 pJ/bit/m^2

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from simulation and the discussion on the results obtained. The flowcharts shown in Figure 2.6, Figure 2.7 and Figure 3.2 were used in carrying out the simulations. Simulations were carried out for two network scenarios; 200*m* by 200*m* and 400*m* by 400***m*****.** Results of node death (network lifetime), energy consumption percentage and number of packets received at the sink were obtained and used to evaluate the performance of the improved protocol. Finally, comparison was done between the results obtained using EEMRP and those obtained using mEEMRP.

4.2 Results

The results obtained through simulations cover percentage of:

a) Node death.
b) Energy consumption.
c) Number of packets received at the BS.

Percentages of these elements are from two different network fields of 200m by 200m and 400m by 400m respectively. Two network field scenarios were used to show that mEEMRP is a scalable routing protocol. These respective results are discussed in the following subheadings:

4.2.1 Node Death Percentage

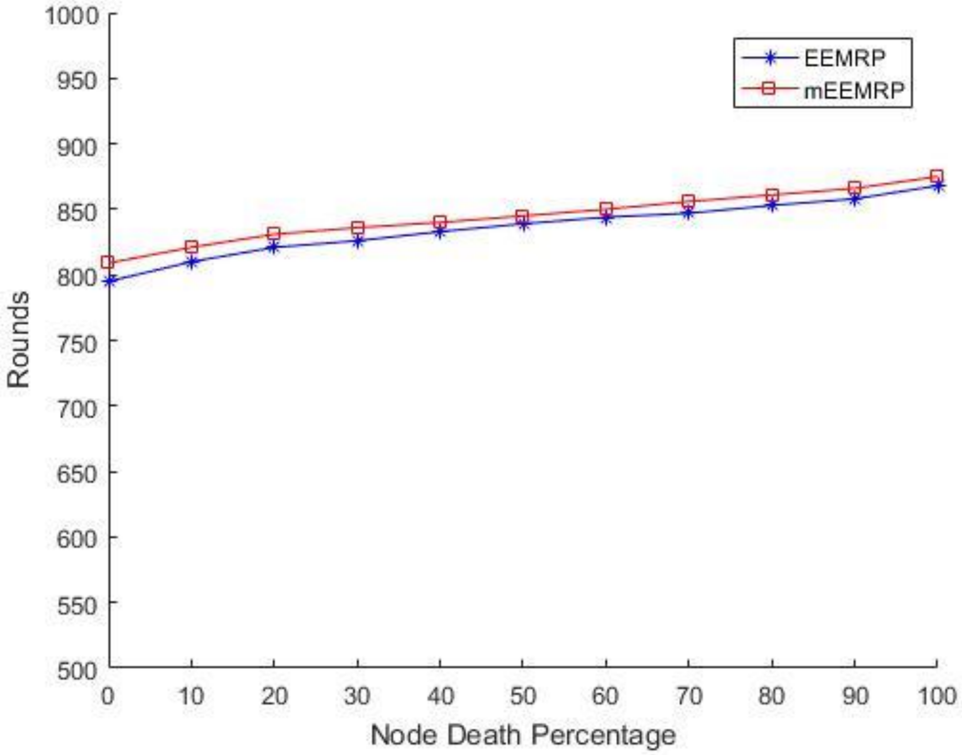

Figure 4.1: Node Death Percentage Plot for 200*m* by 200*m* Network Field

In Figure 4.1, node death percentage is plotted against rounds in a 200*m* by 200*m* network field containing 400 sensor nodes (SNs). The network lifetime is taken as the number of rounds it takes for 100% of the SNs in the network to die. From the figure, using EEMRP as routing protocol, it took 800 rounds for the first node in the network to die (referred to as first node death, FND) as against the 817 rounds it took the mEEMRP routing protocol. Also, using EEMRP, the last node in the network died at 849 rounds (referred to as last node death, LND) as against 864 rounds using mEEMRP. This indicates that by considering residual energy levels of next hop CHs and adopting the election energy threshold, the network lifetime was extended.

It can thus be said that by using mEEMRP, the network lifetime is 2.12% and 1.77% longer than the EEMRP in terms of first node death and last node death respectively.

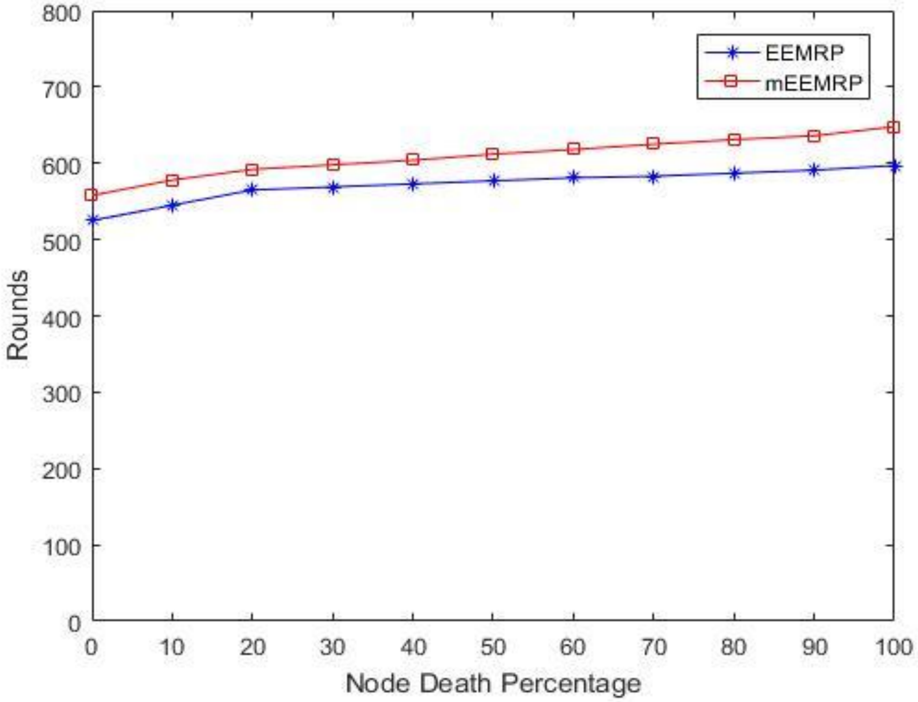

Figure 4.2: Node Death Percentage Plot for 400*m* by 400*m* Network Field

In Figure 4.2, node death percentage is plotted against number of rounds in a 400*m* by 400*m* Network Field containing 400 SNs. From the figure, using EEMRP as routing protocol yields a first node death (FND) time network lifetime of 523 rounds while mEEMRP results in a network lifetime of 564 rounds in terms of FND. That is the time it takes for the first node in the network to die for EEMRP and mEEMRP respectively. Also, using EEMRP, the last node in the network dies at 601 rounds as against 665 rounds using mEEMRP. This indicates that by considering residual energy levels of next hop CHs and adopting the election energy threshold, the network lifetime was extended. It can thus be said that by using mEEMRP, the network lifetime is 7.84% and 10.65% longer than the EEMRP in terms of FND and LND respectively.

4.2.2 Energy Consumption Percentage

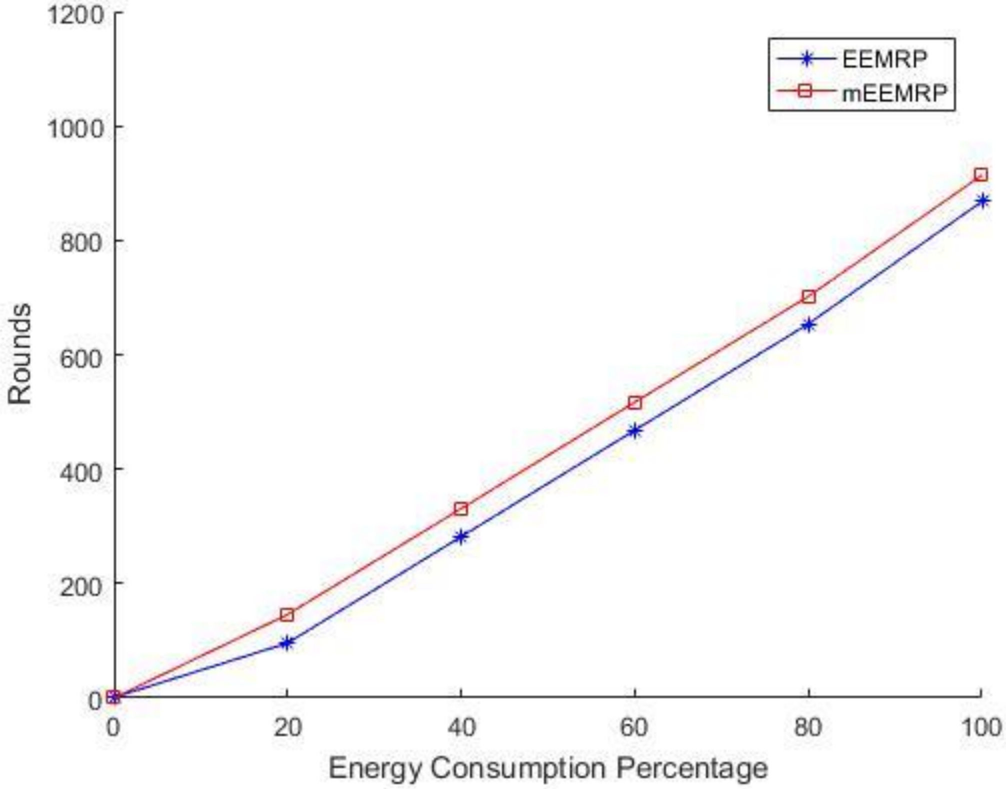

Figure 4.3: Energy Consumption Percentage Plot for 200*m* by 200*m* Network Field

In Figure 4.3, energy consumption percentage is plotted against the number of rounds in a 200*m* by 200*m* network field containing 400 SNs. From the figure, it can be seen that the energy consumption pattern for both routing protocols follow a similar trend. As the number of rounds increase the amount of energy used in the network increases, hence an increase in the energy consumption percentage. Using EEMRP, it can be seen that the energy consumption percentage at different intervals correspond to number of rounds that are considerably less than that of their corresponding energy consumption percentage intervals of mEEMRP. This shows that mEEMRP has a better energy consumption percentage over EEMRP as the residual energy levels of CHs are taken into account as well as their distances during the multi-hop routing of data. From the results obtained, it can be stated that mEEMRP improved the energy consumption percentage by 4.83% over the EEMRP.

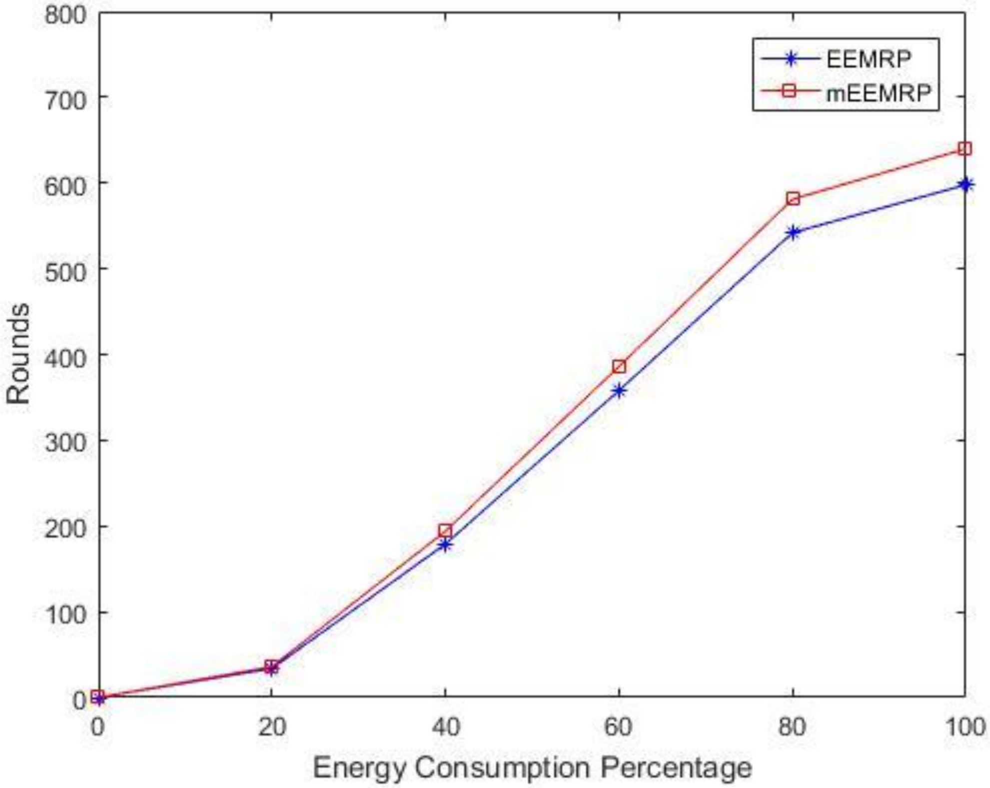

Figure 4.4: Energy Consumption Plot for 400*m* by 400*m* Network Field

In Figure 4.4, energy consumption percentage is plotted against the number of rounds in a 400*m* by 400*m* network field containing 400 SNs. From the figure, it can be seen that there is uniform energy consumption in both EEMRP and mEEMRP up to 20%. This is as a result of the homogeneous nature of the SNs deployed in the network area. During the initial rounds, the SNs have similar energy levels which gives all of them eligibility to participate in the cluster head (CH) selection process and the multi-hop routing of data to the BS. As a result, consumption of energy in the SNs in both protocols is similar. However, as the number of rounds continue to increase and with more SNs consuming their energy during data transmission and reception, the energy levels of the SNs continue to differ thereby restricting the number of SNs that can participate in CH selection and routing of data to the BS. By considering residual energy of CHs during the multi-hop routing of data to the BS in mEEMRP, the energy consumption of SNs is evenly distributed among CHs thereby resulting in a better energy consumption percentage in mEEMRP as against EEMRP. As number of rounds increase, there is an evident difference in the energy consumption of both routing protocols above 20% with mEEMRP performing better than EEMRP. From the results obtained, it can be stated that that mEEMRP performs better than EEMRP by 9.2%. This is as a result of the modification made to the multi-hop routing where energy levels of CHs are considered as well as distance.

4.2.3 Number of Packets Received at the Base Station

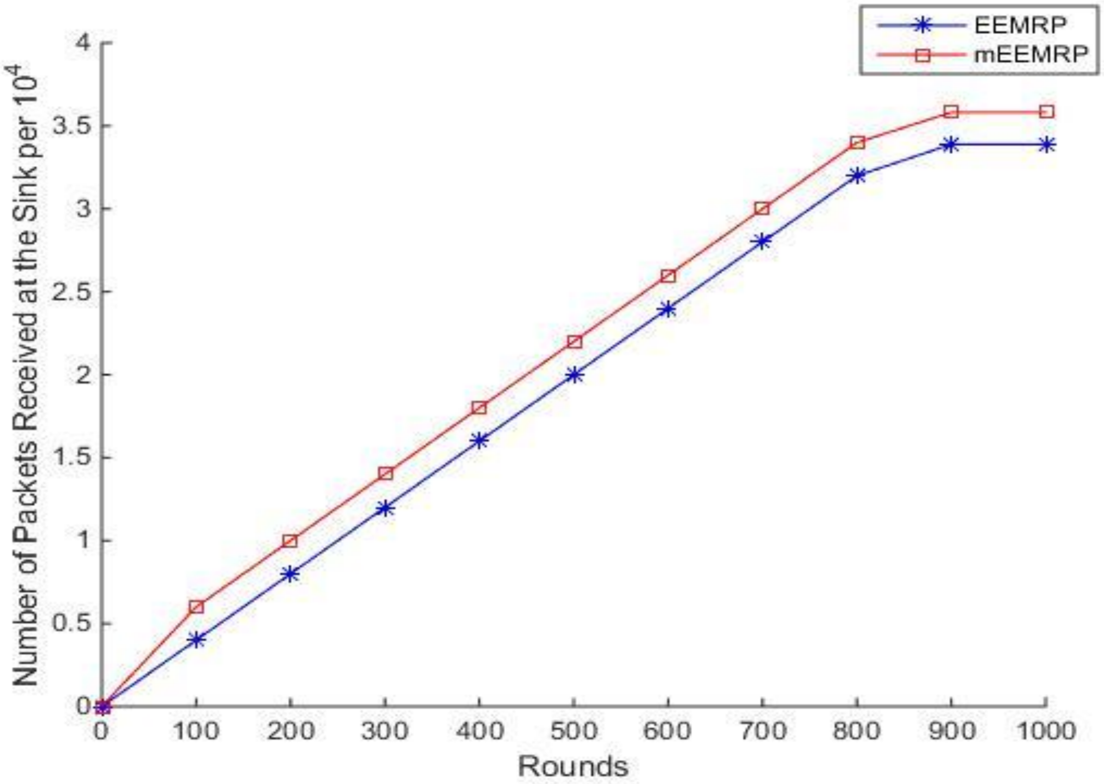

Figure 4.5: Number of Packets Received at the BS Plot for 200*m* by 200*m* Network Field

In Figure 4.5, number of packets delivered at the BS is plotted against number of rounds in a 200*m* by 200*m* network field containing 400 SNs. The number of packets delivered to the BS refers to the number of packets that are successfully received at the designated BS. From the figure, as the number of rounds increase the number of packets delivered at the BS increases. Using EEMRP as routing protocol, it can be seen that the number of packets delivered at the BS at different rounds are considerably less the number of packets delivered at the BS for corresponding intervals for the mEEMRP. This shows that mEEMRP performs better than EEMRP in terms of the number of packets delivered to the BS at different rounds. From the results obtained, it can be stated that mEEMRP performs better than EEMRP by 7.41%. This is because in each round, mEEMRP has more nodes alive to send more data to the BS.

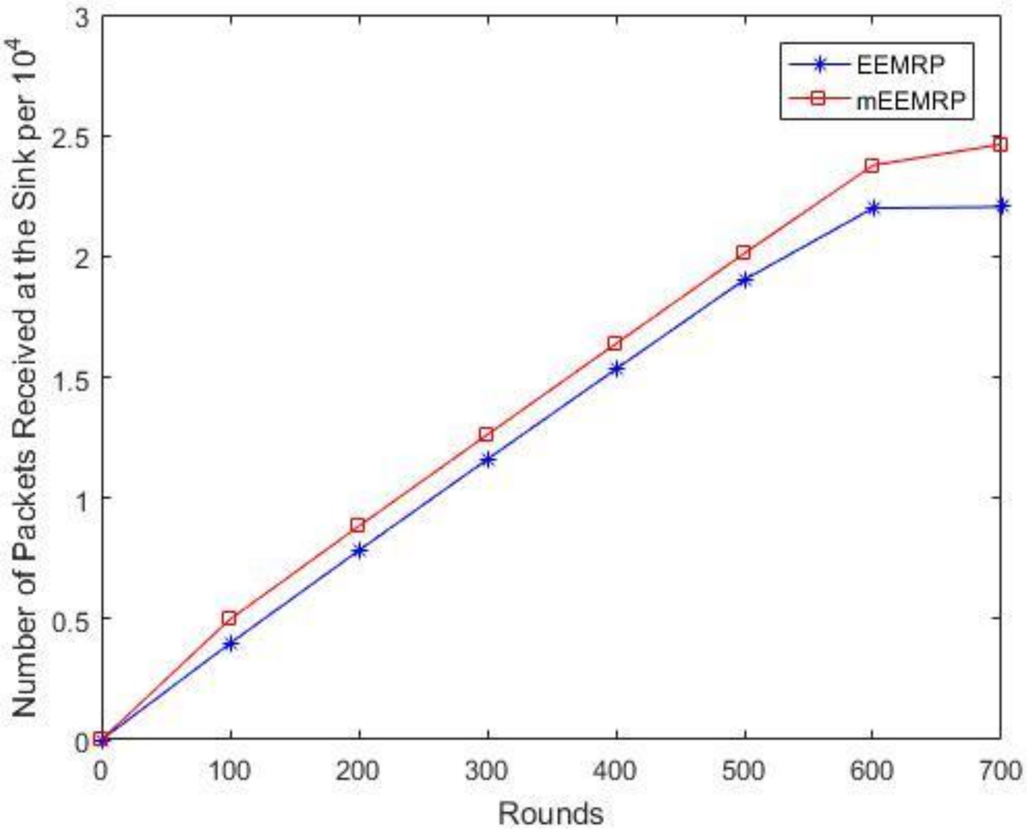

Figure 4.6: Number of Packets Received at the BS Plot for 400*m* by 400*m* Network Field

In Figure 4.6, the number of packets received at the BS is plotted against number of rounds in a 400*m* by 400*m* containing 400 SNs. The figure shows that network lifetime and the number of packets received at the BS are directly proportional. Therefore, as the network lifetime of the WSN increases, the number of packets received at the BS increases. It can also be deduced that as the number of nodes in network reduce, the number of packets being transmitted reduces. This accounts for the straight nature of the plot as the network lifetime of the WSN reaches about 600 rounds in both EEMRP and mEEMRP. In the figure, using EEMRP yields number of packets received at the BS at different rounds that are considerably less that those values achieved by using mEEMRP. This shows that mEEMRP performs better than EEMRP in terms of number of packets received at the BS because, by considering energy during the multi-hop routing of data, the network lifetime is improved. This improvement translates to having more SNs being alive for longer periods to transmit. From the results obtained, it can be stated that mEEMRP performs better than EEMRP by 12.5%.

4.3 Summary of Results

From the results obtained, it can be summarized that mEEMRP performs better than EEMRP in terms of network lifetime, energy consumption percentage and number of packets received at the BS. These improvements ensure efficient operation the WSN. By improving on the energy consumption percentage, network lifetime is extended and as such more data is collected from the network field.

Two network scenarios were adopted to show that mEEMRP is able to perform better than EEMRP as network size increases, that is, mEEMRP is scalable. Performance evaluation of the results obtained from simulation showed that mEEMRP improved network lifetime by 1.77%, improved the energy consumption percentage by 4.83% and improved the number of packets received at the BS by 7.41% in a 200*m* by 200*m* network field over EEMRP. Also, mEEMRP improved network lifetime by 10.65%, improved the energy consumption percentage by 9.2% and improved the number of packets received at the BS by 12.5% in a 400*m* by 400*m* network field over EEMRP.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary

This research work presents the development of an improved multi-hop routing protocol (mEEMRP) in wireless sensor networks (WSNs). From the results obtained, it can be summarized that mEEMRP performs better than EEMRP in terms of network lifetime, energy consumption percentage and number of packets received at the base station (BS). Two network field scenarios, 200*m* by 200*m* and 400*m* by 400*m*, were used to show that mEEMRP is a scalable routing protocol. Simulation results obtained showed that mEEMRP was able to improve the network lifetime, energy consumption percentage and number of packets received at the BS by 1.77%, 4.83% and 7.41% respectively over EEMRP in a 200*m* by 200*m* network field. Also, results obtained from simulations showed that mEEMRP improved the network lifetime, energy consumption percentage and number of packets received at the BS by 10.65%, 9.2% and 12.5% respectively over EEMRP in a 400*m* by 400*m* network field.

5.2 Conclusion

In this dissertation, an improved multi-hop routing protocol in a WSN based on cluster head (CH) load balancing techniques was developed. The improved protocol used an election energy threshold that considered the residual energy (RE) of cluster heads (CHs), as well as the distance between CHs during the multi-hop routing of aggregated data to the BS. The protocol balanced load among the CHs which resulted in improved energy consumption rate, thereby extending the network lifetime. Simulations were carried out on MATLAB R2015b and from the results obtained it can be concluded that mEEMRP improved the network lifetime, energy consumption percentage and number of packets received at the BS of a WSN over EEMRP.

5.3 Significant Contributions

Several researches have been carried out to reduce the energy consumption in WSNs. Energy efficient multi-hop routing protocol (EEMRP) is one of the approached used in reducing energy consumption in WSNs. This approach comes with its challenges. The major challenge of EEMRP is that the multi-hop routing of aggregated data between CHs does not take into consideration the RE of CHs. This approach limits the potential of EEMRP improving the network energy consumption. This research work presents the following significant contributions:

1. The improved multi-hop routing protocol for WSNs based on CH load balancing (mEEMRP) improved network lifetime, energy consumption, and number of packets received at the BS.
2. The following improvements were obtained in a 200m by 200m network field:
   a) 1.77% for network lifetime from 849 rounds to 864 rounds;
   b) 4.83% for energy consumption;
   c) 7.41% for number of packets received at the BS.
3. The following improvements were obtained in a 400m by 400m network field:
   d) 10.65% for network lifetime from 601 rounds to 665 rounds;
   e) 9.2% for energy consumption;
   f) 12.5% for number of packets received at the BS.

5.4 Recommendations for Further Work

1. The work can be extended to consider mitigating interference among neighboring CHs so as to increase the network performance.

2. The routing protocol can be implemented on mobile nodes so as to investigate its efficacy in a different network topology.
3. The work can be extended to larger network field scenarios.

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Appendix A

M-file for Network Area Division and Initialization

```
% Network area division and initialization
for id = 1:N
    x = M*rand;
    y = M*rand;
    [u, v, level] = calGrid(x,y,W,H);
    S(id).ID = id;
    S(id).coord = [x,y];
    S(id).grid = [u,v];
    S(id).gridM = [];
    S(id).level = level;
    S(id).E = E0-(m*a0); %sink broadcast message to all sensor nodes
    S(id).dead = false;
end

save('sensors1.mat', 'S')
% load('sensors1.mat')



% Network is segmented into grids
gg = [];
gID = 0;
gInd = zeros(size(H));
for i = 1:N
    if ~ismember(i, gg)
        gID = gID + 1;
        gridNodes = [];
        for j = 1:N
            if all(isequal(S(i).grid, S(j).grid))
                gridNodes = unique([gridNodes, j]);
                S(j).gID = gID;
            end
        end
        u = S(i).grid(1);
        v = S(i).grid(2);
        G(gID).ID = S(i).grid;
        G(gID).nodes = gridNodes;
        gg = unique([gg gridNodes]);
        gInd(u,v) = gID;
    end
    if numel(gg) == N
        %         gInd =
        break
    end
end
```

Appendix B

M-file for Broadcasting Grid Region Report Message

```
% all node send their grid regions a report message
for i=1:N
    db = M;
    Eij = calEC(S(i).coord, db, a0, p1, p2, db, m);
    k = numel(G(S(i).gID).nodes);
    Er =  k * m * a0;
    S(i).E = S(i).E-Eij-Er;
end
```

Appendix C

M-file for Electing Functional Node (CH)

```
% Electing Functional Node

    for i = aliveNodes
        Ei = S(i).E;
        diO = norm(S(i).coord - O);

        for j = 1 %1:20
            alpha = 0.05 *j;
            if Ei > alpha * Er_bar
                S(i).W0 = ((Ei - alpha * Er_bar)/(alpha *
Er_bar))*(d_bar/diO);
            else
                S(i).W0 = 0;
            end
        end

    end

    for i= 1:numel(G)
        maxW0 = 0;
        for j = G(i).nodes
            if S(j).W0 > maxW0
                maxW0 = S(j).W0;
                G(i).CM = j;
            end
        end
    end
```

Appendix D

M-file for Multi-Hop Routing of EEMRP

```
% Multi-hop routing and stable operation phase

    for l = 1:max(A)
        for p = find(A>=l)

            if l < A(p)

                cCH = G(gInd(p,l)).CH;
                cCH = G(gInd(p,l)).CH;

                % level m nodes transmit to cluster head
                for i = G(gInd(p,l)).nodes
                    if ~isequal(i,cCH) || ~isequal(i,cCH)
                        Eij = calEC(S(i).coord, S(cCH).coord, a0, p1, p2, d0, 
m);

                        S(i).E = S(i).E - Eij;
                    end
                end

                % level m CH recieves, aggregates data and transmit to CM
                k = numel(G(gInd(p,l)).nodes) - 2;
                Er = k * m * a0;
                Ea = k * m * a1;
                Eij = calEC(S(cCH).coord, S(cCH).coord, a0, p1, p2, d0, k*m);
                S(cCH).E = S(cCH).E - Eij - Ea - Er;

                % level m CM recieves and transmit to level m+1 CM
                nl = l+1;
                dCM = inf;
                np = 0;
                for tnp = find(A>l)
                    tnpnlCH = G(gInd(tnp,nl)).CM;
                    d = norm(S(cCH).coord - S(tnpnlCH).coord);
                    if  d < dCH
                        dCH = d;
                        np = tnp;
                    end

                end

                nCH = G(gInd(np,nl)).CM;
                Er = m * a0;
                Ea = m * a1;
                Eij = calEC(S(cCH).coord, S(nCH).coord, a0, p1, p2, d0, m);
                S(cCH).E = S(cCH).E - Eij-Er;
                S(nCH).E = S(nCH).E -Er-Ea;

            elseif l == A(p)

                % level m nodes transmit to base station
                for i=G(gInd(p,l)).nodes
```

```
        Eij = calEC(S(i).coord, O, a0, p1, p2, d0, m);
        S(i).E = S(i).E - Eij;
    end
end
```

Appendix E

M-file for Multi-Hop Routing of mEEMRP

```
% find CH satisfying TnhCH and a distance <= 87.7
                Ev(find(dv > 80)) = 0;
                [val, np] = max(Ev);

                nCH = G(gInd(np,nl)).CM;
                Er = m * a0;
                Ea = m * a1;
                Eij = calEC(S(cCH).coord, S(nCH).coord, a0, p1, p2, d0, m);
                S(cCH).E = S(cCH).E - Eij-Er;
                S(nCH).E = S(nCH).E -Er-Ea;

            elseif l == A(p)

                % level m nodes transmit to base station
                for i=G(gInd(p,l)).nodes
                    Eij = calEC(S(i).coord, O, a0, p1, p2, d0, m);
                    S(i).E = S(i).E - Eij;
                end
```

APPENDIX F

M File for EEMRP

```
function result = EEMRP()
clc
result = [];
 N = 400;                %The number of sensor nodes
M = 200;                %Length of network region
E0 = 0.5;               %Initial Energy of sensor nodes
O = [100, 200];         %location of base station
d_bar = 0.675 * M/2;
m = 2000;               %packet size
a0 = 50e-9;
a1 = 5e-9;
p1 = 10e-12;
p2 = 0.0013e-12;
d0 = 87.7;
n = 4;                  %Rectangle numbers
A = [4 4 4 4];          %Grid numbers of each rectangle
W = [50 50 50 50];      %Rectangle width
H = [70, 50, 50, 30     %Grid width
     60, 50, 50, 40
     60, 50, 50, 40
     70, 50, 50, 30];
% Network area division and initialization
for id = 1:N
    x = M*rand;
    y = M*rand;
    [u, v, level] = calGrid(x,y,W,H);
    S(id).ID = id;
    S(id).coord = [x,y];
    S(id).grid = [u,v];
    S(id).gridM = [];
    S(id).level = level;
    S(id).E = E0-(m*a0); %sink broadcast message to all sensor nodes
    S(id).dead = false;
end
save('sensors.mat', 'S')
% load('sensors.mat')
% Network is segmented into grids
gg = [];
gID = 0;
gInd = zeros(size(H));
for i = 1:N
    if ~ismember(i, gg)
        gID = gID + 1;
        gridNodes = [];
        for j = 1:N
            if all(isequal(S(i).grid, S(j).grid))
                gridNodes = unique([gridNodes, j]);
                S(j).gID = gID;
            end
        end
        u = S(i).grid(1);
        v = S(i).grid(2);
        G(gID).ID = S(i).grid;
```

```
        G(gID).nodes = gridNodes;
        gg = unique([gg gridNodes]);
        gInd(u,v) = gID;
    end
    if numel(gg) == N
        %         gInd =
        break
    end
end
% all node send their grid regions a report message
for i=1:N
    db = M;
    Eij = calEC(S(i).coord, db, a0, p1, p2, db, m);
    k = numel(G(S(i).gID).nodes);
    Er =  N * m * a0;
    S(i).E = S(i).E-Eij-Er;
end
aliveNodes = [1:N];
Er_bar = E0;
round = 1;
deadCount = 0;
while true
    % Electing CM Node
    for i = aliveNodes
        Ei = S(i).E;
        diO = norm(S(i).coord - O);
        for j = 1 %1:20
            alpha = 0.05 *j;
            if Ei > alpha * Er_bar
                S(i).W0 = ((Ei - alpha * Er_bar)/(alpha *
Er_bar))*(d_bar/diO);
            else
                S(i).W0 = 0;
            end
        end
    end
    for i= 1:numel(G)
        maxW0 = 0;
        for j = G(i).nodes
            if S(j).W0 > maxW0
                maxW0 = S(j).W0;
                G(i).CM = j;
            end
        end
    end
    % Electing CH Node
    for i = aliveNodes
        Ei = S(i).E;
        for j = 1
            beta = 0.1 *j;
            if Ei > beta * Er_bar
                S(i).W1 = ((Ei - beta * Er_bar)/(beta * Er_bar));
            else
                S(i).W1 = 0;
            end
        end
    end
```

```
    for i= 1:numel(G)
        maxW1 = 0;
        for j = G(i).nodes;
            if S(j).W1 > maxW1
                maxW1 = S(j).W1;
                G(i).CH = j;
            end
        end
    end
    % % r=[];
    % % for i=1:numel(G)
    % %     r = [r; S(G(i).CM).coord];
    % % end
    % % figure;
    % % plot(r(:,1), r(:,2), '*')
    % % xlim([0, 200])
    % % ylim([0, 200])
     % Multi-hop routing and stable operation phase
     for l = 1:max(A)
        for p = find(A>=l)
            if l < A(p)
                cCH = G(gInd(p,l)).CH;
                cCM = G(gInd(p,l)).CM;
                 % level m nodes transmit to cluster head
                for i = G(gInd(p,l)).nodes
                    if ~isequal(i,cCH) || ~isequal(i,cCM)
                        Eij = calEC(S(i).coord, S(cCH).coord, a0, p1, p2, d0,
m);

                        S(i).E = S(i).E - Eij;
                    end
                end
                  % level m CH recieves, aggregates data and transmit to CM
                k = numel(G(gInd(p,l)).nodes) - 2;
                Er = k * m * a0;
                Ea = k * m * a1;
                Eij = calEC(S(cCH).coord, S(cCM).coord, a0, p1, p2, d0, k*m);
                S(cCH).E = S(cCH).E - Eij - Ea - Er;
              % level m CM recieves and transmit to level m+1 CM
                nl = l+1;
                dCM = inf;
                np = 0;
                for tnp = find(A>l)
                    tnpnlCM = G(gInd(tnp,nl)).CM;
                    d = norm(S(cCM).coord - S(tnpnlCM).coord);
                    if  d < dCM
                        dCM = d;
                        np = tnp;
                    end
                  end
                 nCM = G(gInd(np,nl)).CM;
                Er = m * a0;
                Ea = m * a1;
                Eij = calEC(S(cCM).coord, S(nCM).coord, a0, p1, p2, d0, m);
                S(cCM).E = S(cCM).E - Eij-Er;
                S(nCM).E = S(nCM).E -Er-Ea;

            elseif l == A(p)
```

```
                 % level m nodes transmit to base station
                for i=G(gInd(p,l)).nodes
                    Eij = calEC(S(i).coord, O, a0, p1, p2, d0, m);
                    S(i).E = S(i).E - Eij;
                end
              end
         end
    end
     % calculate average residual energy
    Er = 0;
    for i = aliveNodes
        if S(i).E <= 0
            S(i).dead = true;
            deadCount = deadCount + 1;
            aliveNodes = setdiff(aliveNodes, i);
            u = S(i).grid(1);
            v = S(i).grid(2);
            g = gInd(u,v);
            G(g).nodes = setdiff(G(g).nodes, i);
        else
            Er = Er + S(i).E;
        end
    end
    Er_bar = Er/(N-deadCount);
%
%     round
%     Er_bar
%     deadCount
%     numel(aliveNodes)
%     pause
    Econsumed = N*E0-Er;
    if round>1
        pktRcvd = numel(aliveNodes)/100000+result(round-1,4);
    else
        pktRcvd = numel(aliveNodes)/100000;
    end
    result = [result;  round Econsumed deadCount pktRcvd];
    if deadCount >= 300;
        break
    end
    round = round + 1
end
result;
 % %Energy consumption percentage
% r1 = [0 0];
% for i =2:2:10
%     ind1 = find(result(:,2) <= i*18.5);
%     ind1 = ind1(end);
%     r1 = [r1; i result(ind1,1)];
%
% end
% figure;
% plot(10*r1(:,1), r1(:,2), '*-b')
% ylim([0, 1200])
% ax = gca;
% ax.XTick=0:20:100;
%
```

```
% %Node death percentage
% r2 = [];
% for i =0:10
%     ind2 = find(result(:,3) <= i*30);
%     ind2 = ind2(end);
%     r2 = [r2; i result(ind2,1)];
% end
% figure;
% plot(10*r2(:,1), r2(:,2), '*-b')
% ylim([500, 1000])
%
% %Data transmission capacity
% figure;
% r3 =[0 0];
% for i = 1:10
%     ind3 = find(result(:,1)<= i*100);
%     ind3 = ind3(end);
%     r3 = [r3; i result(ind3,4)];
% end
% plot(100*r3(:,1), r3(:,2), '*-b')
% ylim([0 4])
% ax = gca;
% ax.XTick = 0:100:1000;
end
 function [u, v, level] = calGrid(x,y,W,H)
 W1 = cumsum(W);
H1 = cumsum(H, 2);
 for i=1:numel(W)
    if x<=W1(i)
        u = i;
        break
    end
end
 H1 = H1(u,:);
for i=find(H(u,:)>0)
    if y<=H1(i)
        v = i;
        break
    end
end
 level = v;
 end
 function Eij = calEC(Si, Sj, a0, p1, p2, d0, m)
 if numel(Sj) == 1
    d=Sj;
else
    d = norm(Si - Sj);
end
 if d < d0
    vi = a0 + p1 * d^2;
else
    vi = a0 + p2 * d^4;
end
vj = a0;
 Eij = m * (vi + vj);
end
```

APPENDIX G
M File for mEEMRP

```
function result = mEEMRP()
clc
result = [];
N = 400;                %The number of sensor nodes
M = 200;                %Length of network region
E0 = 0.5;               %Initial Energy of sensor nodes
O = [100, 200];         %location of base station
d_bar = 0.675 * M/2;
m = 2000;               %packet size
a0 = 50e-9;
a1 = 5e-9;
p1 = 10e-12;
p2 = 0.0013e-12;
d0 = 87.7;
n = 4;                  %Rectangle numbers
A = [4 4 4 4];          %Grid numbers of each rectangle
W = [50 50 50 50];      %Rectangle width
H = [70, 50, 50, 30     %Grid width
     60, 50, 50, 40
     60, 50, 50, 40
     70, 50, 50, 30];
% Network area division and initialization
% for id = 1:N
%     x = M*rand;
%     y = M*rand;
%     [u, v, level] = calGrid(x,y,W,H);
%     S(id).ID = id;
%     S(id).coord = [x,y];
%     S(id).grid = [u,v];
%     S(id).gridM = [];
%     S(id).level = level;
%     S(id).E = E0-(m*a0); %sink broadcast message to all sensor nodes
%     S(id).dead = false;
% end
%
% save('sensors.mat', 'S')
load('sensors.mat')
% Network is segmented into grids
gg = [];
gID = 0;
gInd = zeros(size(H));
for i = 1:N
    if ~ismember(i, gg)
        gID = gID + 1;
        gridNodes = [];
        for j = 1:N
            if all(isequal(S(i).grid, S(j).grid))
                gridNodes = unique([gridNodes, j]);
                S(j).gID = gID;
            end
        end
        u = S(i).grid(1);
        v = S(i).grid(2);
        G(gID).ID = S(i).grid;
```

```
        G(gID).nodes = gridNodes;
        gg = unique([gg gridNodes]);
        gInd(u,v) = gID;
    end
    if numel(gg) == N
        %         gInd =
        break
    end
end
% all node send their grid regions a report message
for i=1:N
    db = M;
    Eij = calEC(S(i).coord, db, a0, p1, p2, db, m);
    k = numel(G(S(i).gID).nodes);
    Er =  N * m * a0;
    S(i).E = S(i).E-Eij-Er;
end
aliveNodes = [1:N];
Er_bar = E0;
round = 1;
deadCount = 0;
while true
    % Electing CM Node
    for i = aliveNodes
        Ei = S(i).E;
        diO = norm(S(i).coord - O);
        for j = 1 %1:20
            alpha = 0.05 *j;
            if Ei > alpha * Er_bar
                S(i).W0 = ((Ei - alpha * Er_bar)/(alpha *
Er_bar))*(d_bar/diO);
            else
                S(i).W0 = 0;
            end
        end
    end
    for i= 1:numel(G)
        maxW0 = 0;
        for j = G(i).nodes
            if S(j).W0 > maxW0
                maxW0 = S(j).W0;
                G(i).CM = j;
            end
        end
    end
    % Electing CH Node
    for i = aliveNodes
        Ei = S(i).E;
        for j = 1
            beta = 0.1 *j;
            if Ei > beta * Er_bar
                S(i).W1 = ((Ei - beta * Er_bar)/(beta * Er_bar));
            else
                S(i).W1 = 0;
            end
        end
    end
```

```
    for i= 1:numel(G)
        maxW1 = 0;
        for j = G(i).nodes;
            if S(j).W1 > maxW1
                maxW1 = S(j).W1;
                G(i).CH = j;
            end
        end
    end
    % % r=[];
    % % for i=1:numel(G)
    % %     r = [r; S(G(i).CM).coord];
    % % end
    % % figure;
    % % plot(r(:,1), r(:,2), '*')
    % % xlim([0, 200])
    % % ylim([0, 200])
    % Multi-hop routing and stable operation phase
    for l = 1:max(A)
        for p = find(A>=l)
            if l < A(p)
                cCH = G(gInd(p,l)).CH;
                cCM = G(gInd(p,l)).CM;
                % level m nodes transmit to cluster head
                for i = G(gInd(p,l)).nodes
                    if ~isequal(i,cCH) || ~isequal(i,cCM)
                        Eij = calEC(S(i).coord, S(cCH).coord, a0, p1, p2, d0,
m);

                        S(i).E = S(i).E - Eij;
                    end
                end
                 % level m CH recieves, aggregates data and transmit to CM
                k = numel(G(gInd(p,l)).nodes) - 2;
                Er = k * m * a0;
                Ea = k * m * a1;
                Eij = calEC(S(cCH).coord, S(cCM).coord, a0, p1, p2, d0, k*m);
                S(cCH).E = S(cCH).E - Eij - Ea - Er;
                  % level m CM recieves and transmit to level m+1 CM
                nl = l+1;
                dCM = inf;
                np = 0;
                for tnp = find(A>l)
                    tnpnlCM = G(gInd(tnp,nl)).CM;
                    d = norm(S(cCM).coord - S(tnpnlCM).coord);
                    dv(tnp) = d;
                    Ev(tnp) = S(tnpnlCM).E;
                  end
                % find CM with max energy and a distance <= 80
                Ev(find(dv > 80)) = 0;
                [val, np] = max(Ev);
                  nCM = G(gInd(np,nl)).CM;
                Er = m * a0;
                Ea = m * a1;
                Eij = calEC(S(cCM).coord, S(nCM).coord, a0, p1, p2, d0, m);
                S(cCM).E = S(cCM).E - Eij-Er;
                S(nCM).E = S(nCM).E -Er-Ea;
              elseif l == A(p)
```

```
                   % level m nodes transmit to base station
                for i=G(gInd(p,l)).nodes
                    Eij = calEC(S(i).coord, O, a0, p1, p2, d0, m);
                    S(i).E = S(i).E - Eij;
                end
               end
           end
    end
       % calculate average residual energy
    Er = 0;
    for i = aliveNodes
        if S(i).E <= 0
            S(i).dead = true;
            deadCount = deadCount + 1;
            aliveNodes = setdiff(aliveNodes, i);
            u = S(i).grid(1);
            v = S(i).grid(2);
            g = gInd(u,v);
            G(g).nodes = setdiff(G(g).nodes, i);
        else
            Er = Er + S(i).E;
        end
    end
    Er_bar = Er/(N-deadCount);
%
%     round
%     Er_bar
%     deadCount
%     numel(aliveNodes)
%     pause
      Econsumed = N*E0-Er;
    if round>1
        pktRcvd = numel(aliveNodes)/100000+result(round-1,4);
    else
        pktRcvd = numel(aliveNodes)/100000;
    end
    result = [result;  round Econsumed deadCount pktRcvd];
     if deadCount >= 300;
        break
    end
    round = round + 1
end
result;
 % %Energy consumption percentage
% r1 = [0 0];
% for i =2:2:10
%     ind1 = find(result(:,2) <= i*18.5);
%     ind1 = ind1(end);
%     r1 = [r1; i result(ind1,1)];
%
% end
% figure;
% plot(10*r1(:,1), r1(:,2), '*-b')
% ylim([0, 1200])
% ax = gca;
% ax.XTick=0:20:100;
%
```

```
% %Node death percentage
% r2 = [];
% for i =0:10
%     ind2 = find(result(:,3) <= i*30);
%     ind2 = ind2(end);
%     r2 = [r2; i result(ind2,1)];
% end
% figure;
% plot(10*r2(:,1), r2(:,2), '*-b')
% ylim([500, 1000])
%
% %Data transmission capacity
% figure;
% r3 =[0 0];
% for i = 1:10
%     ind3 = find(result(:,1)<= i*100);
%     ind3 = ind3(end);
%     r3 = [r3; i result(ind3,4)];
% end
% plot(100*r3(:,1), r3(:,2), '*-b')
% ylim([0 4])
% ax = gca;
% ax.XTick = 0:100:1000;
 end
 function [u, v, level] = calGrid(x,y,W,H)
W1 = cumsum(W);
H1 = cumsum(H, 2);
for i=1:numel(W)
    if x<=W1(i)
        u = i;
        break
    end
end
H1 = H1(u,:);
for i=find(H(u,:)>0)
    if y<=H1(i)
        v = i;
        break
    end
end
level = v;
end
function Eij = calEC(Si, Sj, a0, p1, p2, d0, m)
if numel(Sj) == 1
    d=Sj;
else
    d = norm(Si - Sj);
end
if d < d0
    vi = a0 + p1 * d^2;
else
    vi = a0 + p2 * d^4;
end
vj = a0;
Eij = m * (vi + vj);
end
```