ENERGY EFFICIENT CHAIN BASED ROUTING PROTOCOL FOR DETERMINISTIC NODE DEPLOYMENT IN WIRELESS SENSOR NETWORKS

HAYDAR ABDULAMEER MARHOON

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Abstrak

Rangkaian sensor tanpa wayar (WSN) terdiri daripada sensor peranti kecil yang dihubungi secara tanpa wayar untuk tujuan penderiaan dan pengiriman data kepada stesen pengkalan (BS). Protokol penghalaan dalam WSN telah menjadi bidang aktif bagi penyelidik dan industri disebabkan oleh potensi pengiriman data, dan keupayaannya meningkatkan jangka hayat rangkaian, mengurangkan kelewatan, dan penjimatan tenaga nod.Berdasarkan pendekatan hiraki, asas rantaian protokol rutin adalah jenis berpotensi yang berupaya memanjangkan jangka hayat rangkaian dan mengurangkan penggunaan tenaga. Namun, ia masih mempunyai kelemahan seperti kelewatan, kelewahan data, jarak panjang antara jiran, kepala rantaian (CH) pengunaan turus tenaga, dan cerutan. Kajian ini mencadangkan Seragam Asas Rantaian Rutin Protokol (DCBRP) untuk penyeragaman penempatan nod, yang terdiri daripada Mekanisme Pembinaan Tulang Belakang (BCM), mekanisme Pemilihan Ketua Rantaian (CHS) dan mekanisme Sambungan Seterusnya Hop (NHC). Mekanisma BCM bertangungjawab untuk pembinaan rantaian menggunakan pendekatan konsep pelbagai rantaian, dimana ia membahagikan rangkaian ini ke bilangan kluster yang khusus bergantung kepad bilangan jalurnya. Manakala mekanisma CHS bertanggungjawab kepada kepala rantaian, dan pemilihan nod kepala rantaian ditentukan oleh keupayaannya untuk penyerahan data. Pada masa sama, mekanisma NHC bertanggungjawab kepada sambungan hop seterusnya dalam setiap kepala baris berdasarkan kepada tenaga dan jarak antara nod untuk menyingkir nod yang lemah daripada berada dalam rantaian utama. Network Simulator 3 (ns-3) digunakan untuk mensimulasikan DCBRP dan ia dinilai dengan protokol penghalaan terdekat dalam penempatan berketentuan dalam WSN, yang merangkumi protokol Rangkaian Kluster Campuran (CCM) dan Protokol Berasaskan Rantaian Dua Peringkat (TSCP). Hasil menunjukkan bahawa pencapaian DCBRP mengatasi CCM dan TSCP dari segi kelewatan hujung dengan hujung, penggunaan tenaga CH, penggunaan tenaga keseluruhan, jangka hayat rangkaian dan metric tenaga*kelewatan. DCBRP atau salah satu daripada mekanismenya membantu aplikasi WSN dengan melanjutkan hayat nod sensor dan menjimatkan tenaga untuk tujuan pengesanan seberapa lama yang boleh.

Kata kunci: Rangkaian sensor tanpa wayar, Rangkaian berpusat pendekatan, Seragam nod penempatan, Hierarki penghalaan protokol

Abstract

Wireless Sensor Network (WSN) consists of small sensor devices, which are connected wirelessly for sensing and delivering specific data to Base Station (BS). Routing protocols in WSN becomes an active area for both researchers and industrial, due to its responsibility for delivering data, extending network lifetime, reducing the delay and saving the node's energy. According to hierarchical approach, chain base routing protocol is a promising type that can prolong the network lifetime and decrease the energy consumption. However, it is still suffering from long/single chain impacts such as delay, data redundancy, distance between the neighbors, chain head (CH) energy consumption and bottleneck. This research proposes a Deterministic Chain-Based Routing Protocol (DCBRP) for uniform nodes deployment, which consists of Backbone Construction Mechanism (BCM), Chain Heads Selection mechanism (CHS) and Next Hop Connection mechanism (NHC). BCM is responsible for chain construction by using multi chain concept, so it will divide the network to specific number of clusters depending on the number of columns. While, CHS is answerable on the number of chain heads and CH nodes selection based on their ability for data delivery. On the other hand, NHC is responsible for next hop connection in each row based on the energy and distance between the nodes to eliminate the weak nodes to be in the main chain. Network Simulator 3 (ns-3) is used to simulate DCBRP and it is evaluated with the closest routing protocols in the deterministic deployment in WSN, which are Chain-Cluster Mixed protocol (CCM) and Two Stage Chain based Protocol (TSCP). The results show that DCBRP outperforms CCM and TSCP in terms of end to end delay, CH energy consumption, overall energy consumption, network lifetime and energy*delay metrics. DCBRP or one of its mechanisms helps WSN applications by extending the sensor nodes lifetime and saving the energy for sensing purposes as long as possible.

Keywords: Wireless sensor network, Chain-based approach, Deterministic node deployment, Hierarchical routing protocol

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In the Name off Allah, the Most Gracious and Most Merciful

"My Deepest Gratitude is Dedicated to Allah SwT"

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Dedicated to

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and

My family— my wife, Hussein, Abdulameer, Ali and Mohammed, my brilliant sons

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACO	-	Ant Colony Optimization
BCBRP	-	Balancing Chain-Based Routing Protocol
BCM	-	Backbone Construction Mechanism
BS	-	Base Station
CCBRP	-	Chain-Chain Based Routing Protocol
CCM	-	Chain-Cluster Mixed
CCPAR	-	Cluster Chain Based Power Aware Routing
CDT	-	C/C++ Developing Tools
CH	-	Chain Head or Cluster Head
CHS	-	Chain Head Selection mechanism
CRBCC	-	Chain Routing Based on Coordinates-oriented Cluster
CSMA	-	Carrier Sense Multiple Access
DCBRP	-	Deterministic Chain-Based Routing Protocol
DD	-	Direct Diffusion
DRINA	-	Data Routing For in-Network Aggregation
DRM	-	Design Research Methodology
DS-I	-	Descriptive Study 1
DS-II	-	Descriptive Study 2
DSP	-	Deterministic Sensor Placement
DT	-	Deterministic Topology
EAR	-	Energy Aware Routing
ECCP	-	Energy Efficient Cluster-Chain Based Protocol
EECB	-	Energy Efficient Chain Based Routing Protocol

FND	-	First Node Die
GPS	-	Global Position System
HHR	-	Hop-by-Hop Reliability
IEEE	-	Institute of Electrical and Electronic Engineering
IEEPB	-	Improvement Energy Efficient PEGASIS Based
IGR	-	Intra-Grid Random
IoT	-	Internet of Thing
ISO	-	International Organization of Standardization
LEACH	-	Low Energy Adaptive Clustering Hierarchy
LL	-	Long Link
LND	-	Last Node Die
LR-WPAN	-	Low Rate Wireless Personal Area Network
MAC	-	Media Access Control
MN	-	Member Node
NHC	-	Next Hop Connection mechanism
NS-3	-	Network Simulator 3
ON	-	Ordinary Node
OSI	-	Open System Interconnection
PEGASIS	-	Power Efficient Gathering in Sensor information System
PS	-	Perspective Study
QoS	-	Quality of Service
RC	-	Research Clarification
REC+	-	Reliable and Energy Efficient Chain-Cluster Protocol
RNs	-	Relay Nodes
RPB	-	Rotation PEGASIS Based Routing Protocol

SAT	-	Secure Aggregation Tree
SN	-	Sensor Node
SPIN	-	Sensor Protocol Information Negotiation
TCP	-	Transport Control Protocol
TDMA	-	Time Diffusion Media Access
TSCP	-	Two Stage Chain Protocol
UDP	-	User Datagram Protocol
WSN	-	Wireless Sensor Network

CHAPTER ONE
INTRODUCTION

1.1 Background

Wireless Sensor Network (WSN) as the name implies, refers to a number of small sensor devices, which are connected to each other wirelessly. WSN applications are widely used in several areas. These include industrial domain, military institutions, habitat monitoring, environmental establishments and disaster management [1]. The main components of a WSN are the sensor nodes which have many limitations in its characteristics. These include, the power resources, computational capabilities, bandwidth and memory [2]. These nodes have the capability of communicating with each other. The communications are also established between one or more super nodes known as the Base Station (BS). This BS is thus connected to the Internet. Each distinct node has a built in sensor devices for a specific task (one or more task). The sensors consists of a radio module used in sending data through the wireless medium, a micro controller for processing, and the power supply component for providing the necessary energy for all mechanism in the devices [3]. Typically, batteries are the main source of power in the sensor nodes and consequently, due to its deployment, recharging seems a difficult task. WSN nodes also have particular level of algorithms intelligence used in collecting and transmitting data to the BS [4].

Routing is one of the most pertinent perplexing issues that directly affect the performance of WSN. Proportionally; the main goal of the routing protocols in WSN is to deliver all sensing data to the base station with minimum power consumption to extend the lifetime of the network's nodes. Different factors have been identified to affect the performance of the WSN which are related to the routing protocols. These include scalability, energy consumption, bandwidth, data aggregation, redundancy, multipath, end-to-end delay, and localization [5].

However, in line with the network structure, the routing protocols in WSN are mostly categorized into three: *flat*, *hierarchical*, and *location-based* routing protocols. Within the flat routing protocols, all nodes perform the same task in the network, which normally exhibit the flooding technique in transmitting data to the BS. The flat topology is effective in a small-scale network. Location-based routing protocols on the other hand, uses real time applications. This is also called position-based protocol due to its ability of exhibiting the data transmission with respect to the geographical positions [5], [6].

Moreover, the hierarchical routing protocols perform different tasks as it relates to the node mode of communication. Part of the distinction between the flat protocol and the hierarchical is the existence of one or more Cluster Heads (CH) in every network cluster. The main function of CH is to serve as a medium of collecting data from the output environment. This also aid in aggregating the data from the normal nodes, which are used to send messages between CHs or with the BSs as the scenario may be. The rest of the nodes are thus referred to as the ordinary node (ON), or member node (MN). The ON and sometimes MN are also used as traversing channels to CH [7], [8]. Figure 1.1 depicts the forms of routing in WSN.

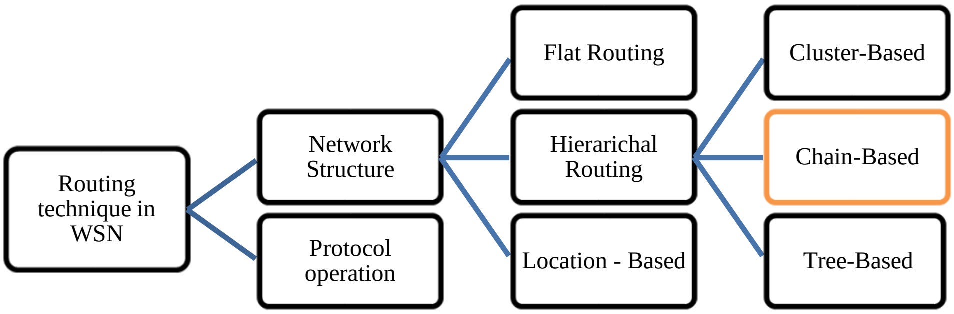


Figure 1.1. Routing Protocols in WSN

As depicted on the Figure above, cluster-based, chain-based and tree-based protocols are the main categories of hierarchical routing protocols [9]. In Figure 1.2, the node relationship with the BS explains the architectural composition as clusters in WSN are further presented. This shows the node clustering as each node is connected with BS in wider perspective. In cluster-based protocols, one or more nodes are selected to be CH. Other nodes are connected in a position closer to the CH, these nodes act as the MNs. An example of a cluster-based protocol include Low Energy Adaptive Clustering Hierarchy (LEACH) [10]. The principal concept is a tree-based structure where each of all sensing data is sent from children (sensor node) to their parents [11]. Data Routing For in-Network Aggregation (DRINA) is also an example of a tree-based routing protocol [12]. The nodes are framed in a chain-based protocol, arranged in a chain form topology where one of the nodes is dedicated as a CH to aid in transmitting data to the BS. While different routing protocols in WSN are discussed in the literature review, chain-based protocols seem most promising among others in terms of better energy consumption and network lifetime [13], [14].

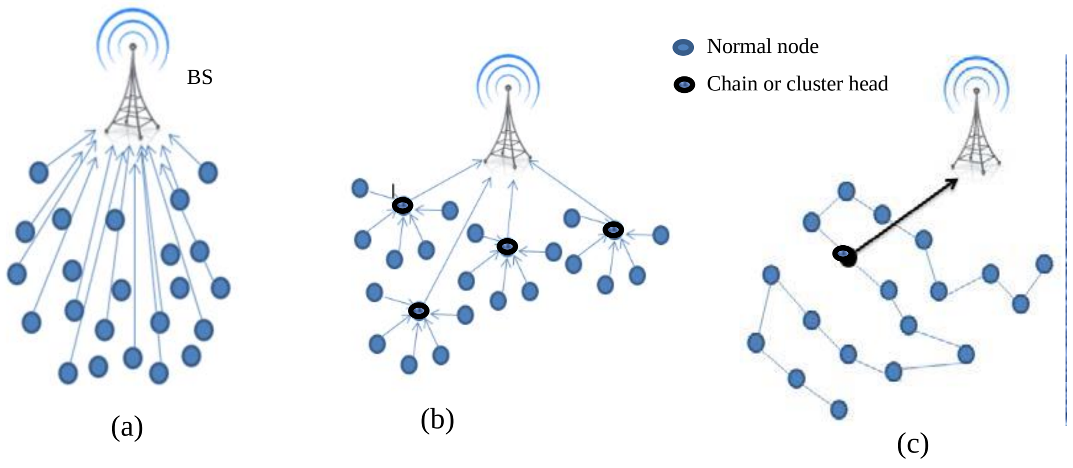


Figure 1.2. Nodes Connections in WSN

Furthermore, node deployment is extremely application dependent, and thus related to better energy consumption and network lifetime for all nodes. Typically, there are two illustrious methods used for nodes deployment in WSN. The first being the *deterministic*, this defines the deployment of the nodes manually in predetermined areas to meet the requirements of its applications. The second strategy is randomly deployed for all nodes, these are used in the areas where manually installation is not readily applicable [15], [16].

1.2 Research Motivations

In the past few years, Wireless Sensor Networks (WSN) have become an active area of research due to its broad and growing applicability. However, WSN nodes have limitations in power management resources, which lead researcher to develop alternative routing protocols in order to reduce excessive energy consumption, and to prolong networks lifetime to proffer reliable data delivery.

In addition, design for efficient routing protocols is considered as one of the key challenging issue that directly impact the performance of WSN. Chain-based routing approach have better potential and are more promising when compared to other types of routing protocols due to its energy saving features in communication and lesser power consumption [14]. Nevertheless, this approach needs much attention to address some of the ongoing issues. Achieving this would make progressive improvement to the present efficient chain based routing protocol. Hence, the CH selection factors and efficient ways to aggregate data from nodes to BS with shortest chain topology are part of the current challenges for researchers to pursue. Because of, they have a significant influence on extending network lifetime, reducing delay and saving energy in WSN.

1.3 Problem Statement

The communication part of nodes in WSN is considered as the main part which consumes the sensor node energy, more than the other parts. This is because of the needed energy for transferring one bit is equal to energy required for executing 3000 processes [17]. Efficient Routing protocol is one of the most important issues that directly influence the overall performance of WSN in the communication. The main goal of routing protocols in WSN is to ensure the total operation of delivering sensing data to the base station with minimum power consumption. So doing, helps to maximize the WSN lifetime. Chain based routing technique is performed with minimum power consumption, and prolong network lifetime [14], [18]. Furthermore, chain based technique definitely save the communication energy consumption using low radio power in order to connect nodes to the closest neighbor [11].

However, chain based routing protocols are suffering few drawbacks in terms of performance. In transmitting data from one node to another in the multi hop, the challenge is seen in the likeliness of more delays in a long chain [19], [20]. Multi hop will enforce sensor node to receive, process and deliver neighbors data so, that will increase delay in the network. Furthermore, the nodes spend more energy on redundant data until they are delivered to the base station, especially when data comes through nodes that are positioned far away from the sink [1], [14], [21], [22]. Additionally, long chain makes particular nodes in the network to dissipate energy quickly, which shortens the lifetime of the network [23].

Furthermore, the chain is subjected to failure in chain heads, or in main head node in an event that all network data are sent to the single leader node. This node is usually charged with the responsibility for delivering all network data to base station [20]. The main node spends its energy very quickly and more than others. Therefore, the main node needs to be selected efficiently and carefully to perform the designated role. Single leader node selection according to the power consumption perspective results in bottleneck problems in the network [1], [24], [25]

In addition, chain construction starts from the farthest node in the sensing area using the Greedy algorithm. Greedy algorithm considers distance as the only precondition when choosing the next hop connection. This therefore, ignores the residual energy in the nodes. Therefore, nodes that have lower energy die early, causing all previous nodes to be disconnected and thus lose data [26]. This is also called the less robustness in chain based routing protocol [20].

1.4 Research Questions

Based on previous discussion, the followings are the research questions for this study:

1- How to construct multi chain of nodes for deterministic deployment to avoid the single and long chain, eliminate delay, and redundant data?

2- How to select the appropriate number of chain heads and suitable chain head nodes to avoid bottleneck and energy consumption problems in the chain heads?

3- How to select suitable next hop node in the chain to avoid link failure caused by nodes that have low energy level?

1.5 Research Objective

This research is intended to design a chain base routing protocol for deterministic nodes deployment in WSN. The DCBRP protocol can keep the network away from long chain issues using multi chain concept to avoid delay and redundant data. When this is set, the consideration of selecting CHs in a proper weight base method that would choose a specific number of CHs to mitigate the bottleneck problem and chain heads failures. Finally, this research is aimed at having the potential of overcoming the problem inherited from the greedy algorithm concept in choosing next hop connection. The overall depends on the distance and residual energy. Such intended protocol will be pursued with the following research objectives:

1- To design a Backbone Construction Mechanism (BCM) that build the network chains by using a multi chain concept to mitigate the impact of the long chain;

2- To design Chain Heads Selection mechanism (CHS) for CHs selection with specific number of CHs using the weight base method to avoid CH failure and bottleneck problem;

3- To design Next Hop Connection mechanism (NHC) in every vertical chain by using distance and energy factors to avoid link failure during data transfer; and

4- To develop DCBRP routing protocol by combining the BCM, CHS and NHC mechanisms and evaluate the performance of DCBRP protocol with the existing routing protocols for deterministic nodes deployment to reduce energy consumption and prolong network lifetime in WSN.

1.6 Scope of the Research

Based on the network structure, this research focuses on the hierarchical routing protocols with chain based routing approach in deterministic nodes deployment in WSN. This research will be conducted in domains that require the deployment of sensor nodes in fixed position in grid setting. Furthermore, the DCBRP is partly restricted to the network layer where the data is received from the upper layers in the same way regardless of the applications. Different mechanisms can thus work together in building the DCBRP routing protocol. The entirety of this research deals with three mechanisms that directly affect the performance of routing protocols in chain based WSN. The first mechanism is used for constructing chain while, the second deals with the CH selection, and conclusively, last is used in choosing the next hop connection. Network Simulator 3 (ns-3) would be used to evaluate the DCBRP routing protocol with careful selection of performance metrics of delay, energy consumption, network lifetime and energy*delay for both approach data fusion and without data fusion. This research focus on applications in agriculture, such as pest control, irrigation, fertilization, horticulture and greenhouse monitoring, which have a continuous data transmission to BS (as considered by [18], [27], [28]) and the multimedia contents are out of scope.

1.7 Significance of Study

The main purpose of this research is to establish an energy efficient routing protocol for wireless sensor networks, which helps to prolong the network lifetime, and reduce delay and the power consumption. Furthermore, the DCBRP routing protocol consists of three mechanisms, first is the Backbone Construction Mechanism (BCM). This will be responsible in constructing the chains in the network. While, the main goal of the BCM will build the chains in multi chain concept, therefore it will reduce the delay required for data delivering. Second is the Chain Head Selection Mechanism (CHS) which is responsible in saving the CH energy by preventing chain head failure in early rounds of delivering the network data without packets loss to the BS. CHS mechanism thus, important to reduce the power consumption of chain head nodes, and prolong the network lifetime especially in First Node Die (FND). Third is Next Hop Connection Mechanism (NHC).

The main goal is to prevent weak node (has low energy) selection in the main chain and avoid the link failure during data collections.

According to the above mechanisms, the DCBRP can significantly transfer the network data from source to destination with reliable path, less power consumption, less delay and overall ability in prolonging the network lifetime. Consequently, this study is significantly important to the applicability of WSN specifications. Especially with the limitation of power supply and sensor nodes stationary characteristics, it is therefore a requirement for many sensor network applications [29]. This protocol can be used where energy efficiency and timely delivery of data is required, where all nodes have same initial energy. Furthermore, DCBRP protocol will help WSN particular areas in agriculture such as pest control, irrigation, fertilization, horticulture, greenhouse monitoring, and many more [30], [31] by extending the sensor nodes lifetime and saving their energy for sensing purpose as long as possible.

1.8 Thesis Outline

This thesis is organized in six chapters, which are summarized below as thesis chapters' outline:

Chapter One: This chapter presents the introduction of the study and an overview of the thesis. The chapter covers study the motivation, importance of WSN, and its routing schemes. Research problem statement, research questions and objectives, the research scope and significance are widely covered in details as such.

Chapter Two: This chapter presents the literature review on wireless sensor networks. The chapter begins by presenting past researches on nodes deployment strategies (most popular WSN applications) and illustrates the hierarchical approach of routing protocols alongside its advantages and challenges. In addition, this chapter also discusses specific chain base routing protocols in details. Finally, this chapter illuminates the most related chain base routing protocol in deterministic node deployment and presented a table for further review and summation of the literature review.

Chapter Three: This chapter presents the research methodology used by this research to attain the slated objectives. Research tools and pertinent performance metrics are discussed with its equations.

Chapter Four: This chapter is dedicated to the design of DCBRP routing protocol in details. Wide details of the design, implementation, verification and validation of its mechanisms BCM, CHS and NHC are covered.

Chapter Five: This chapter discusses the performance evaluation of DCBRP with closest routing protocols in terms of delay, energy consumption, network lifetime and energy*delay metrics, the evaluation will use the data fusion and without data fusion approach for more comprehensive evaluation of DCBRP protocol behaviors for delivering data.

Chapter Six: This chapter presents the research conclusion with highlight the research contributions, limitation and future direction related with this research.

CHAPTER TWO
LITERATURE REVIEW

2.1 Background

WSN is regarded a challenging field by most stakeholders especially the industry and researchers. On the last few decades, its applications have been growing steadily in different areas [7] such as habitat monitoring, industrial company, health and medical, military issues, disasters prediction and management, security, agriculture and others [17], [23]. Sensor network connects between computational, physical and human environment. Data are collected from environment by sensors and delivered to the base station using node networking. This process is repeated in every round. In general, WSN consists of a large number of small devices called sensor nodes (SNs). All sensor nodes have the ability of sensing data, processing and communicating wirelessly with each other. These sensor nodes have limitations in memory, power resources, bandwidth, and computational capability [7]. In addition, the super node has unlimited resources which is referred to as the base station (BS) that works as a sink.

Basic sensor node architecture consists of four units [32]: (a) sensing unit that is responsible for sensing the outside environment according to its capability, for example temperatures, humidity, light, and so on, (b) processing unit, memory, and all computing and processing operations. These are also different according to nodes types and have limited ability, (c) communication unit that makes the necessary connections and network. This unit has the largest power consumption among all node units, (d) the power (battery) unit that works as energy supplier for all units in sensor node. Figure 2.1 shows the basic architecture for sensor node in WSN.

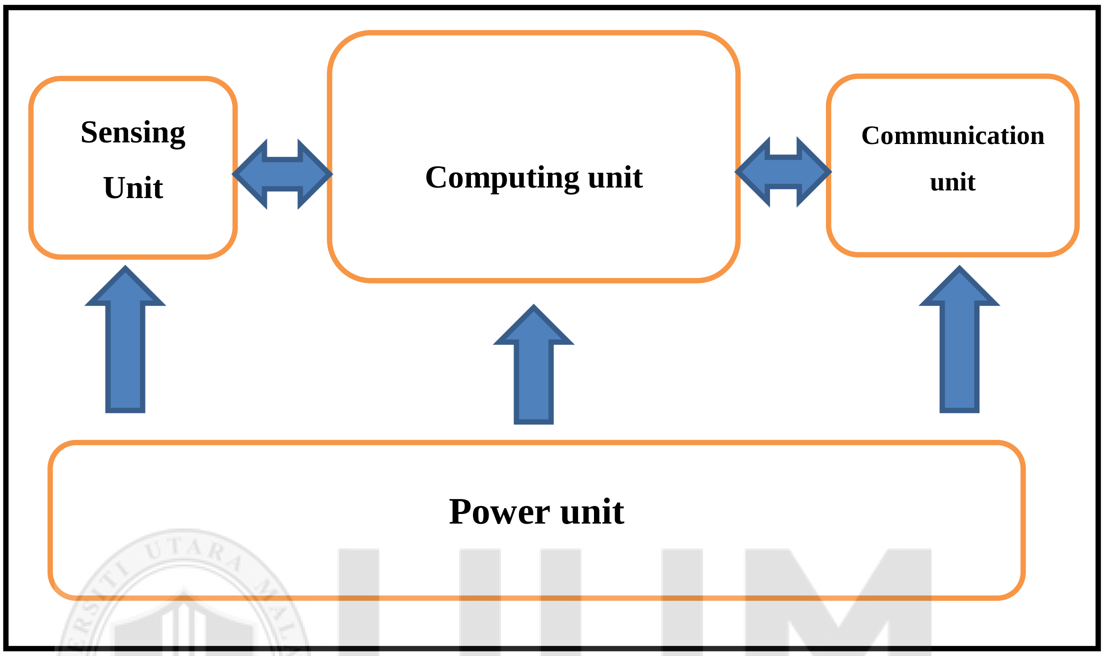


Figure 2.1. Basic Architecture for Sensor Node in WSN (Adopted From [33])

Many factors can directly affect the performance of WSN. These factors include the ways sensor nodes are deployed in the sensing area (randomly or deterministic deployment); the routing protocols that are used to create a suitable directions to the base station. The node selected for chain head or cluster head will discussed in detail in this Chapter.

2.1.1 WSN Sensor Deployment

The sensors deployment method can affect the performance of the entire WSN. Choosing good sensors deployment strategy can reduce the node redundancy, minimize the network overall cost, prolong the network lifetime, and reduce the complexity of data fusing and routing [32], [34]–[36]. Therefore, the main issue in sensors deployment is its effective use to increase the coverage area, provide the efficient nodes connection, and energy saving.

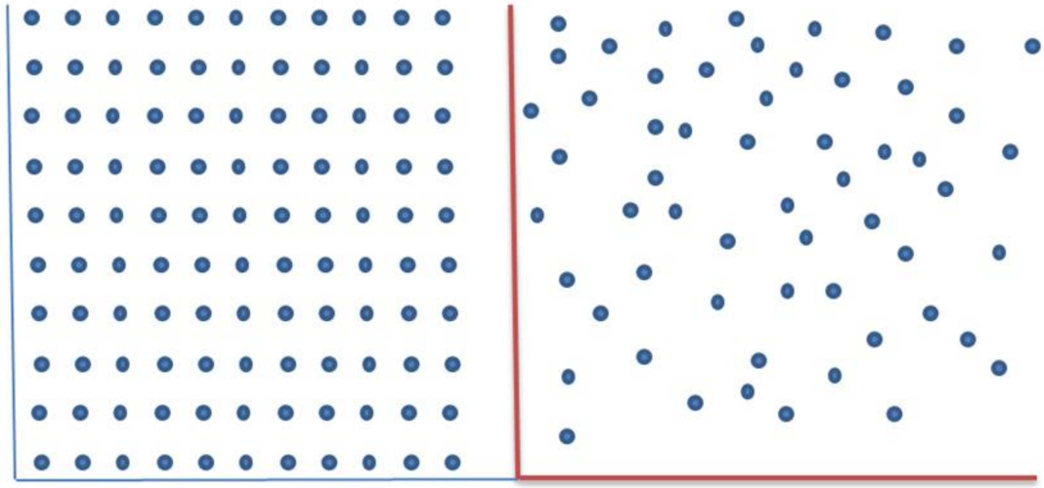
Damuut and Gu in [37] classified node deployment into two main types. The first is deterministic and second is non-deterministic nodes placement. A node placement scheme depends on the following three elements:

1- *Application area*: Deterministic is more suitable for healthcare, scientific measurements, and domestic appliances. It is common in surveillance applications such as in agricultural area [37]. However, non-deterministic is preferred in military, forest fire detection and disaster applications.

2- *Type of sensor*: In some cases nodes deployment depends on nodes characteristics such as weight, size and material etc.

3- *Cost*: Nodes cost, maintenance cost, and installation cost are really important parameters in choosing deterministic or non-deterministic deployment.

Figure 2.2 shows the number of nodes that are deployed in Deterministic and Random ways in the sensing area:



(a) Deterministic (b) Random

Figure 2.2. Deployment Strategies in WSN

Deterministic strategy is the best placement of nodes in the sensing area and sensor location which will not change during network lifetime [34]. Moreover, Deterministic Sensor Placement scheme (DSP) [38] is a common scheme in nodes deployment to meet specific performance objectives with effective positioning of nodes [39]. The advantages of DSP are its utilization for sensors devices, controllable network topology, more efficient routing protocols and coverage performance. However, time wastage during installation is still the main drawback in deterministic nodes deployment.

In addition, random deployment (or non-DSP) strategy is used in some areas which have time-sensitive applications due to its quick deployment and self-organization that present a pertinent drawback in network lifetime in terms of the number of nodes death in every round [37].

2.1.2 OSI and WSN Stacks

International Organization for Standardisation (ISO) proposed the Open System Interconnection (OSI) during the first of WSN protocol development [38]. However, WSN do not have seven layers like OSI model. In reality, it only has limited layers, like Application, Transport, Network, Data Link, and Physical [40], [41] as shown in Figure 2.3

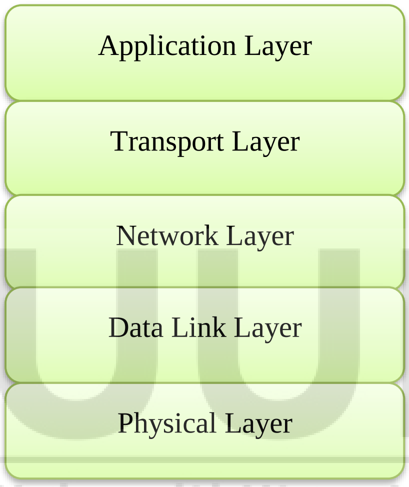


Figure 2.3. WSN Protocol Stack

Each layer has independent working task with others, the first layer is the physical layer and is responsible to define and manage the connection between devices and its communications medium. In addition, it also functions to perform the carrier frequency generation, frequency selection, signal detection data encryption, and modulation.

The second layer is the data link layer. It provides service that allows multiple nodes to access and share communications medium. This layer performs various functions such as making a reliable delivery, medium access control, error correction and error detection. The third layer of the protocol stack is the network layer, which is responsible for drawing the communications path from nodes to base station, and routing the packets from source to destination along the paths. Different designed routing protocols have different functions. These include energy awareness, service quality, delay reduction, and extending the network lifetime or hybrid of them.

The fourth layer is the transport layer which is responsible for reliable data delivery with popular transport protocols, i.e., User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) for connectionless and connection oriented, respectively, according to adopted applications.

Last but not least, the fifth layer is the Application layer which is related with users of the system and have many applications for different functions [40]. Section 2.1.4 shows more details about the applications in WSN.

2.1.3 IEEE 802.15.4 Standard

IEEE standard 802.15.4 (in 2003) was clearly designed as a new standard for devices and applications. It has limited resources in power consumption capability, that is, Low-Rate Wireless Personal Area Network (LR-WPAN) [40]. The IEEE 802.15.4 standard specifies the physical layer and MAC layer for the use of LR-WPANs (IEEE 2003). The first version of IEEE 802.15.4 was published in 2003.

The Physical layer consists of the radio transceiver and the equivalent low-level control mechanism. The MAC layer gives the definitions of data transmission by accessing the physical layer. While the specifications have limited resources, the WSN application is a simple protocol, which can reduce the system overhead. The IEEE 802.15.4 architecture is simple and allows the developers to design the application software at low-level requirement, which can interact directly with the data transfer and free data collision [42]. Further comprehensive detail on IEEE 802.15.4 LR-WPAN can be seen in [43].

2.1.4 WSN Applications

The sensor technologies are widely used in many applications related with particular life of the human nowadays. Figure 2.4 illustrates some of the most important applications of WSN in different areas and domains [41], [42], [44]. The specific characteristics of application require specific type of sensors, routing protocol, and deployment strategies (deterministic or random). The environment and energy consumption are important to choose proper sensor types for applications due to the serious problem of energy for the network design [42].

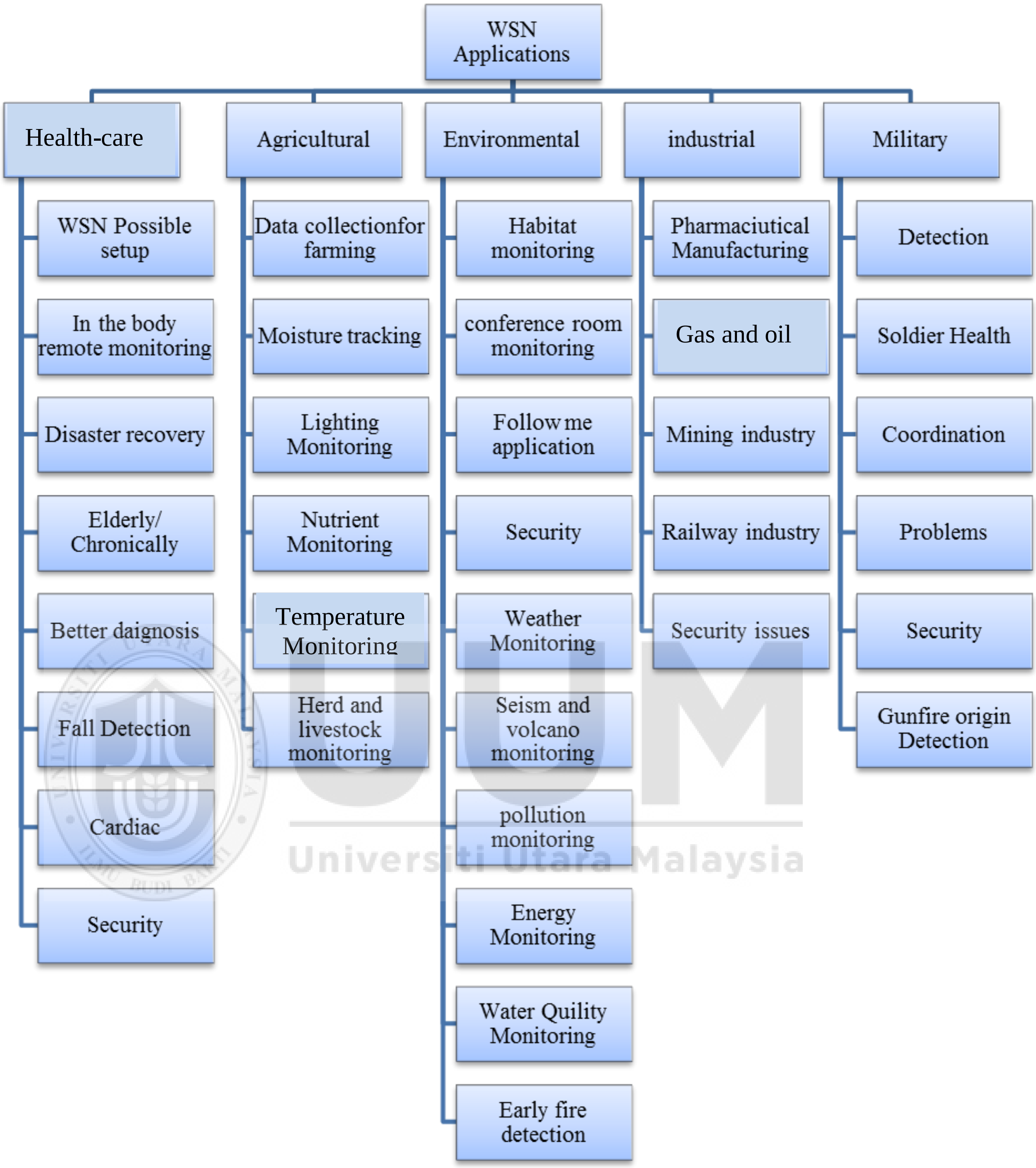


Figure 2.4. WSN Applications in Different Area

Agriculture is an important aspect of human civilization. With the increase in human population and the rising demand for food, a lot of effort is invested in developing and enhancing methods to increase the production of food. One such effort is the utilization of advanced technologies. Today, information technology is complimenting the use of scientific technology in the agricultural domain. Information technologies such as satellite navigation, grid computing, sensors, context aware and ubiquitous computing advocate the decision making and monitoring processes of the agricultural area and industry [45]. The use of technology such as sensor networks has vastly helped the agriculture positively. There are different types of terminologies used to describe technology on sensors such as Farming by Inch, Smart Agriculture, Precision Agriculture and Farming, Information-Intensive Agriculture, and Site Specific Crop Management. However the basic conceptualisation of all these remains the same [46].

The function of sensors is to gather environmental and physical data. The sensor collects information that is useful for recognising environmental situation, people and locations, as they define an object or environment [46]. Furthermore, the WSN applications have been developed to help particular areas of agriculture such as pest control, irrigation, fertilization, horticulture, greenhouse monitoring, and many more [30], [31]. It is necessary that in all applications the sensor node is deterministic deployed in the sensing area. This is important to allow larger range coverage which consequently reduces the amount of nodes in one particular sensing area [37].

2.2 Routing in Wireless Sensors Networks

Routing in WSN is a demanding and challenging issue that can affect the network performance and lifetime. It has more challenges than traditional ad hoc network as a result of the WSN's characteristics [47]. Firstly, WSN have more constrains in processing capability, power resources, communication bandwidth. Secondly, the data aggregations of all sensor nodes can cause data redundancy. Thirdly, due to heavy overheads on WSN, it is difficult to create global addressing schemes [7]. Finally yet importantly, communication in WSN is usually many-to-one instead of many to many, or peer-to-peer in other networks. Routing in WSN must consider all sensor nodes properties, and able to deliver data as well as maintaining efficiency of its power consumption. Quality of Service (QoS) is less important than energy conservation in WSN because it is directly related to network lifetime.

Some of the routing protocols in WSN are dependent on specific intelligent algorithms to route their data to BS. This requirement is similar to ant colony optimization (ACO) [48]–[50], genetic algorithm [51], and simulate annealing [52]. These are widely classified into three categories based on network structure. These include: Flat, location-based, and hierarchical routing protocols [53]–[55]. Flat utilizes different routing algorithm to others, and all sensor nodes within flat performs the same roles and have the same abilities. All data are sent by nodes in multi hop like flooding until the data reach the sink [56]. Many protocols are proposed under the flat category such as Flooding and Gossiping [57], sensor protocol information via negotiation (SPIN) [58], Rumor [59], Directed Diffusion

(DD) [60], Stateless Routing [61], Energy- Aware Routing (EAR) [62], Sequential Assignment Routing [63], Gradient-Based Routing [64] and others.

As compared to other categories, the hierarchical routing protocols have the potential to maintain the node energy more than other types [8]. Nodes in this approach play different tasks within different rounds. Ordinary nodes will sense data and transmit it to the group leader (cluster Head chain head). CHs relay collected data from the ONs, and send it to the base station. More details on hierarchical routing protocols will be discussed in the next section.

2.3 Hierarchical Routing Protocols

The basic idea in hierarchical routing protocols is to divide the nodes into different groups [1]. Each group is called *cluster* or chain which has certain number of nodes as normal nodes to perform the sensing. Cluster head node relays data to the base station. Within this protocol, selecting cluster head and forming the cluster are of primary importance [65]. Hierarchical routing technique can potentially save the networks energy using multi hop method to deliver data to the sink. In addition, it also uses data aggregation and data fusion to reduce the number of packet to the destination [21]. The routing protocol design is very important to prolong the power consumption [66].

Hierarchical routing protocols have many significant advantages compared to flat protocol strategies. These include the following: [67]:

a- It uses limited bandwidth channel and reduces the demand on bandwidth;

b- It reduces the total energy consumption on data transmission;

c- It reduces the maintenance overhead in routing and topology;

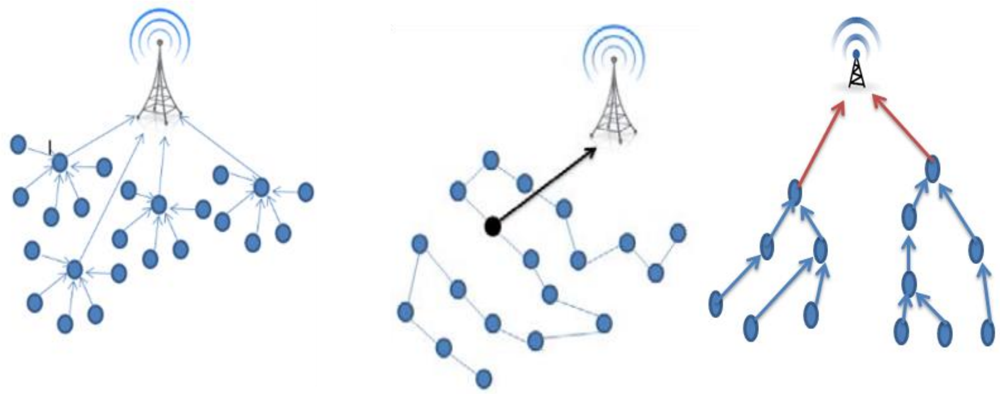
d- It minimizes redundant data during aggregation and fusing process;

e- It reduces routing table by dividing the nodes for the number of cluster with limited linked connection;

f- It eases network management and is more scalable; and

g- It prolongs the network lifetime and reduces total power consumption.

Hierarchical routing protocols are divided into three categories. These include cluster-based, chain-based, and tree-based routing protocols [9]. In cluster, nodes are organized as groups and one cluster head is assigned to every cluster. While in chain-based, every node is connected to its neighbor only in the form of chain with one or more than one chain head. Nodes are used to connect these chains to the base station. The principal concept in tree-based is that all sensing data is sent only from children (sensor nodes) to their parents. Salam and Ferdous in [68] made a comprehensive data aggregation survey on tree-base routing protocols like secure aggregation tree (SAT) [69], PEDAP [70], WST-LEACH [71], EADAT [72], MST [73], TCCAA [74], and others. Figure 2.5 shows the types of hierarchical routing protocols in WSN and their forms:



(a) Cluster-based (b) Chain-based (c) Tree-based

Figure 2.5. Hierarchical Routing Protocols in WSN

2.4 Cluster-Based Routing Protocols

There are four stages in most cluster-based routing protocols [67], which consist of (1) cluster head (CH) selection, (2) cluster formation, (3) data aggregation, and (4) data communication. In addition, there are two states in every round: First is the setup state which consists of CH selection, and cluster formation phases. Second is the steady state which performs data aggregation, as shown in Figure 2.6.

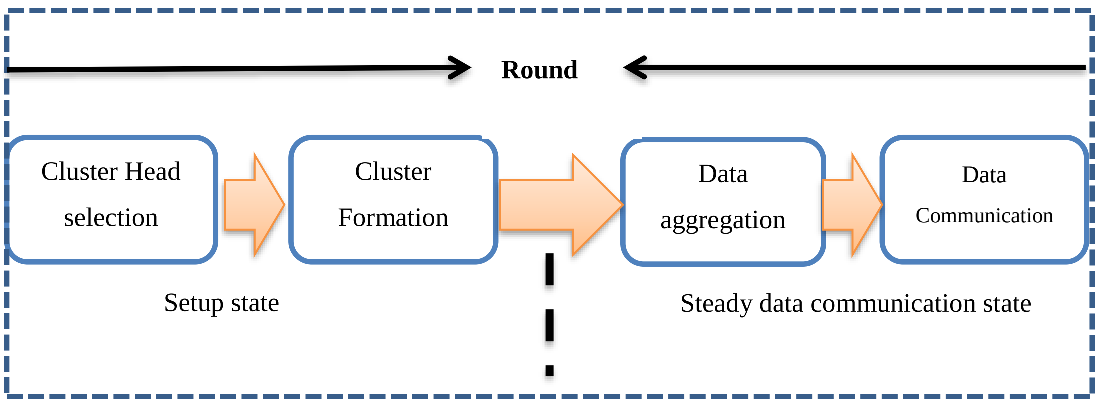


Figure 2.6. Clustering Process in one Round

The nodes in cluster-based protocols can be divided based on their roles in the network into three types:

a- *Member nodes*: The main role of these nodes is to sense data from outside environment and to send data to the cluster head.

b- *Relay nodes*: These nodes are responsible for relaying data from member nodes to the cluster head and to the next hop or to CH. Relaying nodes can only be found in multi-hop protocols and are sensing the data in the same time.

c- *Cluster head nodes*: Leader of cluster collects sensing data from member nodes and sends them to the network's sink. In some protocols, these nodes send data to next hop until reaches the base station.

2.4.1 Low-Energy Adaptive Clustering Hierarchy

Many routing protocols are proposed under cluster-based approach. For example, Low-Energy Adaptive Clustering Hierarchy (LEACH) proposed by [10] is the most famous cluster-based routing protocol in WSN. Basic idea in LEACH protocol is to divide nodes into many clusters and select CH for every cluster. These two steps are executed in the setup phase while data aggregation and data communication are settled in the second steady state phase. LEACH is self-organized protocol and CH selection is based on random function and threshold for the desired percentage of CHs. CH selection is made in every round and after CH decision is made, it sends the advertise message to all neighbor nodes. The signal strength of every node decides that which cluster should join the existing round and send membership message to its cluster head. Normal topology for LEACH is shown in Figure 2.7. LEACH does not need the global information of the network. It is completely a distributed approach. Many protocols are built based on LEACH. These are called the LEACH family. These include E-LEACH [75], TL-LEACH [76], V-LEACH [77], LEACH-C [78], T-LEACH [79], W-LEACH [80], LEACH-FL [81] and MR-LEACH [82].

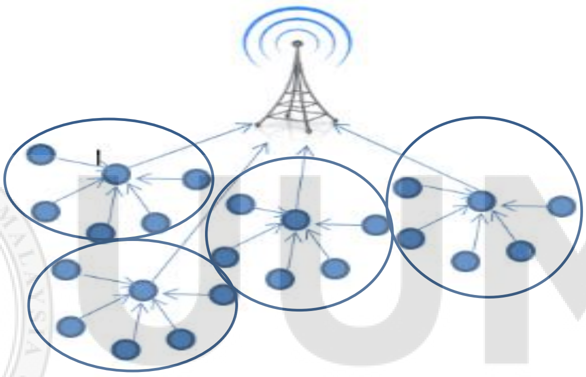


Figure 2.7. Typical Topology for LEACH

LEACH protocol has many advantages. These include: (1) energy consumption by CH will be equally distributed among nodes because the node which is chosen as CH will not be cluster head until all nodes take this task; (2) LEACH uses TDMA as MAC protocol and this prevents clusters from unnecessary collisions; and (3) normal nodes in LEACH protocol do not need to be directly connected to the base station. It is connected to its CH only. Therefore, LEACH has the potential to save energy as it has the shortest distance between CH and member nodes. As such, it avoids data redundancy [83].

However, there are also drawbacks in LEACH protocol which are as follows: (1) In some cases, in spite of the long distance when CHs are directly connected to base station in inter-connection, this will dissipate CHs energy more quickly. (2) In CH selection, despite the fact that rotation selection happens in every round, this selection is based on probabilistic usage without energy consideration. Therefore, some nodes will function as CH even though they have low energy; and (3) the dynamic cluster construction in every round adds extra overhead.

2.4.2 Energy-Efficient LEACH

According to Energy-Efficient LEACH (EE-LEACH) [84], the formation of clusters in sensor networks highly depends on the time taken to receive the neighbor node message and the residual energy. The protocol is divided into rounds and each round is triggered to find out the optimal CH. The clusters are formed based on the following steps:

Step 1: neighbor information retrieval: The neighbor node information is sensed by broadcasting the beacon messages throughout the network.

Step 2: Perform sorting algorithm: The sorting algorithm is performed to retrieve the list of all neighbor nodes about its hop distance. The list is sorted into descending order.

Step 3: candidate for cluster: When its two- hop neighbor node is not enclosed, it analyzes all the members of stage 2 one-by-one and crowns any one two-hop neighbor for choosing as a candidate for the cluster.

Step 4: calculate the residual energy of neighbor nodes: Finally, the sorting algorithm is executed based on the residual energy of the neighbor nodes.

The computations are based on the following simplifications: assume that the intra cluster transmission stage is long and the entire data nodes can forward the data to their CH. When inter cluster transmission is long enough, all CH having data can forward their data to the BS. The CH needs to perform the data aggregation and compression before forwarding the data to the BS. The optimal probability of a sensor node is elected as a CH based on the function of spatial density. The clustering approach is optimal in the sense that overall energy utilization is minimal such that optimal clustering is greatly dependent on the energy model.

EE-LEACH reduces the end-to-end delay, increases packet delivery ratio and reduces the energy consumption as compared to the energy-balanced routing protocol (EBRP) and the basic LEACH protocol. However, its drawback is that it depends on the residual energy when chooses the cluster members. Furthermore, CH election is based on the function of spatial density and ignores the distance with the BS.

2.5 Chain-Based Routing Protocols

The underlying idea in chain-based routing protocols is to connect all nodes with each other like chain(s) to reduce the power consumption in the transmission part of sensor devices by minimizing the radio power coverage. This idea is successful because of its objective to keep the unnecessary power consumption for wide area. When a node needs to connect and transmits its data to the closest node only, chain head(s) collect data from all chain members using multi hop method to deliver data to the base station with single hop method. Mamun in [14] did comprehensive comparison of different logical topologies in WSN. Cluster-based, tree-based, flat and chain-based topologies use common performance metrics such as energy dissipation and balancing, network life time, resource spend per message delivery, and others. This study shows that chain-based topology outperforms other topologies in terms of total energy consumption, energy distribution, load distribution, network lifetime, and topology management overhead.

Based on the fact that "energy is the main consideration in analyzing routing protocols in WSN" [85], chain-based routing protocol is considered to be more promising than other routing protocol approaches due to its primary ability and features in power saving and extending network lifetime [13], [18], [86].

2.5.1 Chain-based Routing Protocol Characteristics

There are many common characteristics in the hierarchical routing protocols. It can conclude that some are specifically employed for chain-based routing protocols in WSN because of the following reasons:

a- Every node in the network is connected to the closest neighbor node only in a chain form;

b- The connection type in intra-connection is multi-hop; on the other hand, inter-connection uses single or multi hop to reach the BS;

c- It extends the network lifetime with low power consumption;

d- It reduces the overhead coming from dynamic cluster formation;

e- All nodes can send Hello massage to the BS in the first round to collect all nodes information;

f- Chain-based network structure suffers from delay caused by Long Link (LL) and data redundancy (repetition of data transmissions);

g- Division of Long Link (long chain) into sub-level of small chain is good to avoid data redundancy;

h- Residual energy is not considered when selecting CH in some protocols, while others consider this as CH selection condition;

i- Base Station is stationary and exists in only one base station for all protocols;

j- It can reduce the energy consumption when nodes send data only to their closest neighbor; and

k- Energy distributions in chain-based routing protocols are even due to little energy used per bit utilized for communication.

2.5.2 Power-Efficient Gathering in Sensor Information Systems

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) in [27] is a protocol that begins the chain-based approach concept for routing protocols in the WSN. During initialization, the chain construction starts from the furthest node in the topology and begins to communicate with only closest neighbor. All nodes use the greedy algorithm to organize themselves as a chain. The greedy algorithm considers only the physical distance in order to select next hop in every node and ignores the residual energy in the neighbor that causes short node's lifetimes [87]. Alternatively, the BS can calculate the chain after broadcasting the chain's information to all sensor nodes in the network. Every 100 rounds, the chain leader (how it connects to the BS) will be changed from one node to the other randomly. The main point in this randomization is to ensure that the dead nodes are randomly located in this network. Moreover, when the chain head dies, the network starts constructing new chain and selects a new chain head randomly. Normal topology for PEGASIS is shown in Figure 2.8

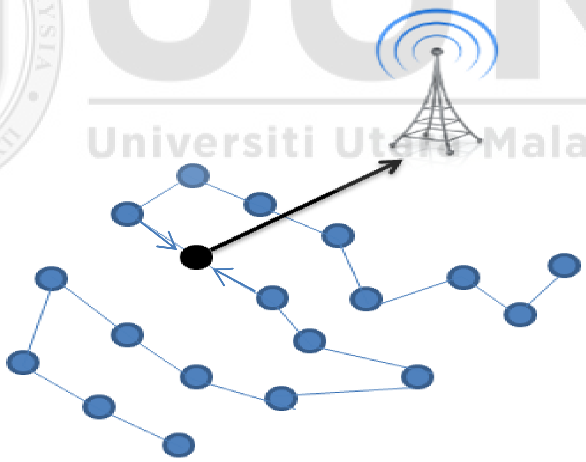


Figure 2.8. PEGASIS Protocol Topology

However, in the first improvement of chain leader (or chain head), selection comes from the same authors when making threshold on the neighbor distance to make sure that this leader has only little energy instead of trying to reduce the neighbor distance in some way.

PEGASIS uses the same radio model that was used in LEACH protocol, which is the first order radio model. In the first order model, the energy for receiving or transmitting data is $E_{elec} = 50nJ/bit$ and the dissipated energy in the amplifier is$E_{amp} = 100pJ/bit\ /m^2$. Therefore, equations 2.1 and 2.2 can be used to calculate the energy costs of k-bit in transmitting and receiving, which are as below [10], [23], [27]:

For transmitting

$$E_{TX}(k,d) = E_{TX-elec(k)} + E_{TX-amp}(k,d)$$

$$E_{TX}\ (k,d) = E_{elec} * k + E_{amp} * k * d^2 \qquad (2.1)$$

For receiving

$$E_{Rx}(k) = E_{Rx-elec}(k)$$

$$E_{Rx}(k) = E_{elec} * k \qquad (2.2)$$

Where k is the number of bits and d is the distance between nodes.

PEGASIS has an important advantage in terms of power saving, that is coming from reducing the clustering overhead energy in every round [88] and making sure that every node is connected with only neighbor so that the procedure will reduce power consumption through radio signal part. Moreover, every node in PEGASIS fuses the neighbor data with its data to reduce the amount of data transfer to BS based on the Equations 2.1 and 2.2. This fusing will reduce energy cost in both sides (receiving and transmitting).

PEGASIS has some drawbacks as well. Firstly, it assumes that all nodes can directly be connected to the BS, while in practical these nodes use multi-hops to reach the BS. Secondly, PEGASIS uses greedy algorithm to construct its chain, it uses distance parameter to select next hop connection. It is like traveling salesman problem and greedy doing good performance in some cases. However, greedy makes long distance connection in different topologies and this will make some nodes depleted their energy quickly. Second issue in greedy is that it uses distance only to choose the next hop connection without considering the remaining energy in this node. This will cause some weak points in the chain and may disconnect some of the nodes from the chain. Furthermore, PEGASIS is not suitable for deterministic deployment topologies because the long chain disadvantage comes from the single chain construction.

Single leader in the network will cause a bottleneck problem. All network data must be delivered to the base station through this node, which spends its energy very quickly. The chain will save more energy, add more delay and redundant data accrue in long link chain. The distance between node and BS is not considered when selecting the chain head. Therefore, this will cause CH to spend most of its energy when its location is far from the BS [89].

2.5.3 Chain Routing Based on Coordinates-oriented Cluster

Chain Routing Based on Coordinates-oriented Cluster (CRBCC) proposed in [90] first divides the network topology into many Y coordinator clusters with equal number of nodes (approximately). Next, it uses the simulated annealing (SA) algorithm instead of greedy algorithm in PEGASIS to build the intra-connection as chain form in every cluster. Every chain elects a leader in X coordinator and these leaders construct the main chain using SA algorithm [91]. Then, once the leader of leader chain node is selected randomly, it will send data to the base station directly. Figure 2.9 shows CRBCC topology.

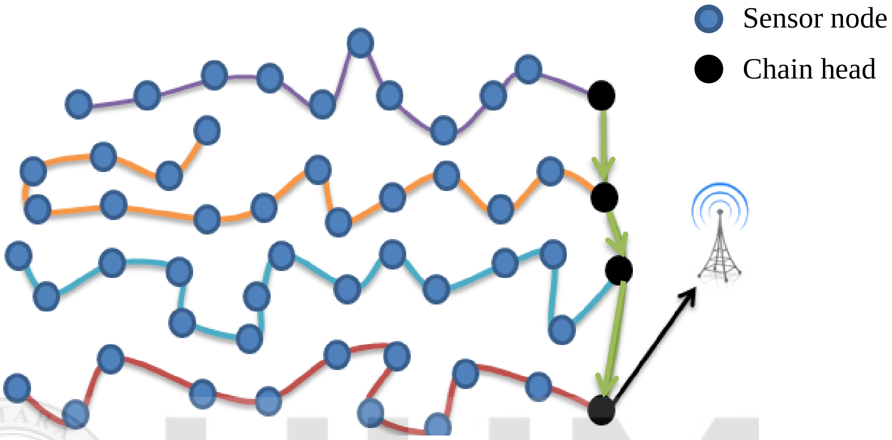


Figure 2.9. CRBCC Routing Protocol

CRBCC reduces the data delivery time from nodes to BS. This is achieved by dividing the chain in PEGASIS to multi parallel chains depending on horizontal positions (avoid Long Link problem). Based on chain-based approach, it minimizes the power consumption in data aggregation. Greedy algorithm used in PEGASIS is locale search that does not provide global optimum links between nodes, so, CRBCC will use another heuristic algorithm for this issue.

CRBCC has unavoidable drawbacks in terms of chain leader election in the top of chains. Moreover, these nodes will deplete their energy more quickly than others without any active procedure to select another chain leader during the network lifetime. Random selection of the main head can cause unlucky nodes to be selected twice or more than twice compared with others that have never been selected. Nevertheless, randomized selection can be replaced by choosing effective parameters like rest energy or node distance with base station. These parameters can make leader selection more efficient and prolong the network lifetime.

2.5.4 A Reliable and Energy-Efficient Chain-Cluster Based Protocol

A Reliable and Energy-Efficient Chain-Cluster Based protocol (REC+) proposed in [25] aims to perform the maximum reliability in a multi hop network by calculating the best position for the CH and the proper shape and size of the cluster. REC+ is the first protocol that considers transmission reliability, energy efficiency, and intra-cluster delay together to build the cluster and select the cluster head.

The operation of REC+ is divided into three phases: (1) cluster formation phase, in this phase REC+ assumes that the BS has all information about nodes in terms of position and energy. The BS divides the sensor nodes in the network into clusters based on Y-coordinator. Figure 2.10 shows one of these clusters.

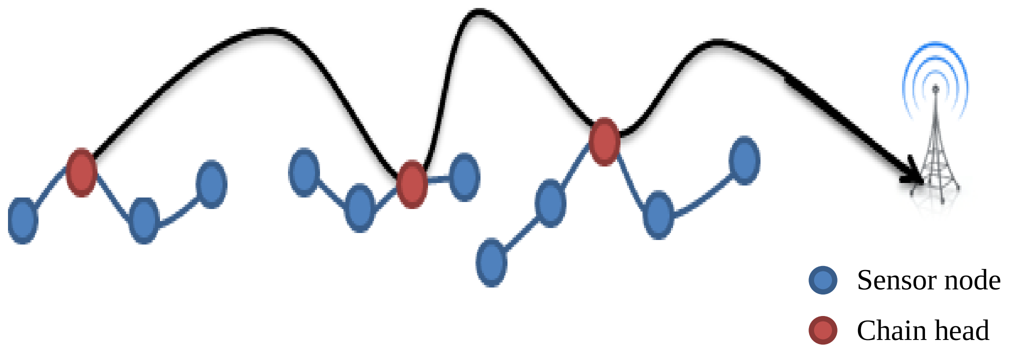


Figure 2.10. REC+ Routing Protocol

(2) Cluster Head Selection and chain-cluster forming phase: as opposed to other algorithms, REC+ chooses the chain heads first then assigns its member nodes. BS selects CHs based on residual energy divided by initial energy. Hop-by-hop reliability (HHR) is reported to the BS by nodes to ensure that quality link is created. That node will be the first node in this cluster when 0^{EER} (end-to-end reliabilities) is more than the threshold 0^{EER}. Nodes play multi hop (chain) method to reach its CH and another threshold tries to avoid long link (LL) in every cluster-chain, which is delay. This is second threshold, which prevents delay in the LL. Furthermore, Relay Nodes (RNs) are assigned to some powerful nodes (in terms of energy and position) by BS to relay CHs data when CH cannot directly send its data to the next CH (next hop). To select proper RN, BS calculates the maximum Power Level (PL) of every CH that can be used for coverage, then assigns RN for this CH when it is needed. All BS calculations will be repeated when any node dies during the network lifetime.

Third phase in REC+ is steady state phase. In this phase every node will sense data and send it to its neighbor. The node fuses the neighbor data with its data (if any) then deliver it to CH. CH uses RNs to ensure that the data reach BS in reliable way. Any significant changes occurred in nodes' parameters can affect the link quality or some nodes below the threshold 0^{EER} , the BS recalculates CHs and clusters shape as well.

The advantage of REC+ is to use two thresholds to create cluster and select the CH, one for energy and the other for delay. However, REC+ makes many more overhead on the network during its three phases. Moreover, REC+ assumes that all nodes can be connected directly to the BS to setup the first and second steps and this cannot always be applicable in practical networks. The important notice for REC+ is that in random deployment many nodes may be allocated in the specific areas which may cause some of the clusters to have many nodes and others a few nodes when Y-coordinator is used to create clusters.

2.5.5 Balanced Chain-Based Routing Protocol

Balanced Chain-Based Routing Protocol (BCBRP) in [92] decreases the energy consumption in the network by dividing the network area into small equaled sub area, therefore, the number of the sub-area will be equal to j^2 (j= 1,2,3,….) . After that BCBRP assigns header and leaf nodes in every sub-area. Nodes are located in boundary of this sub-network; furthermore, leaf node makes connection between its sub-network and previous sub-network, while header node makes connection between its network with next sub-network (notice that first sub-network does not have leader node and last sub-network does not have leaf node). After that, in every sub-area, chain will be constructed using minimum spanning tree algorithm instead of greedy in PEGASIS to ensure that minimum chain distance will be constructed in each network. Figure 2.11 shows BCBRP chain construction in four sub-networks.

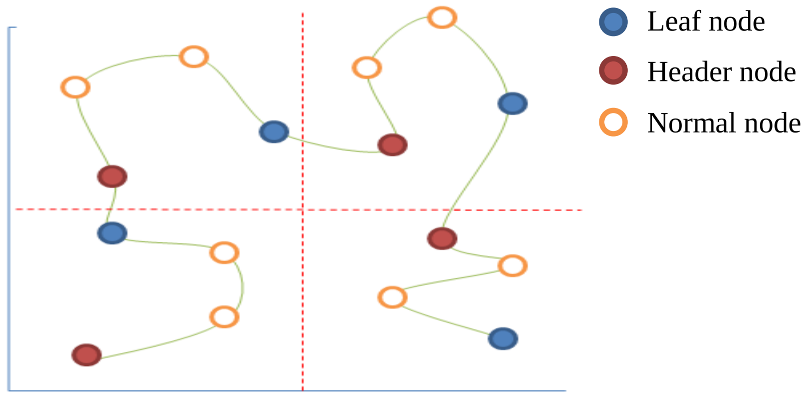


Figure 2.11. BCBRP Routing Protocol

When node death occurred during network lifetime, only this sub-network will take chain reconstruction. Moreover, the main head node (which is connected with BS) will be selected randomly from the larger sub-network in the sensing area.

BCBRP reduces the power consumption by minimizing the overall chain link with minimum spanning tree algorithm instead of greedy, which has many drawbacks. However, single chain in BCBRP and random selection of the main head are noticeable drawbacks that can affect the performance of this protocol.

2.5.6 Chain-Based1 & Chain-Based2

Chain-Based1 routing protocol [93] deploys all nodes randomly in the sensing area. Multi chain directed to the base station is created from the last node to the first node, as shown in Figure 2.12(a). The sensing area is divided into m sub-areas based on X coordinator). All nodes on the top chain will be chain heads and will use single hop to reach the BS. Chain will be updated when node depletes its energy during the network lifetime. Every node senses data and transmits it to the closest neighbor.

Moreover, this node fuses data with its data and sends it to the next hop until reaches the BS.

Chain-Based2 is an improved version of the Chain-Based1 protocol. It has the same concept in the intra-connection and does the same deviation in Chain-Based1, except it creates main chain from all chain heads, as shown in Figure 2.12(b). At first, the nearest node (in the main chain) from BS is responsible for sending all network data to the BS. Then during the network lifetime, node that has more energy will play role as the main head and will be connecting to the BS.

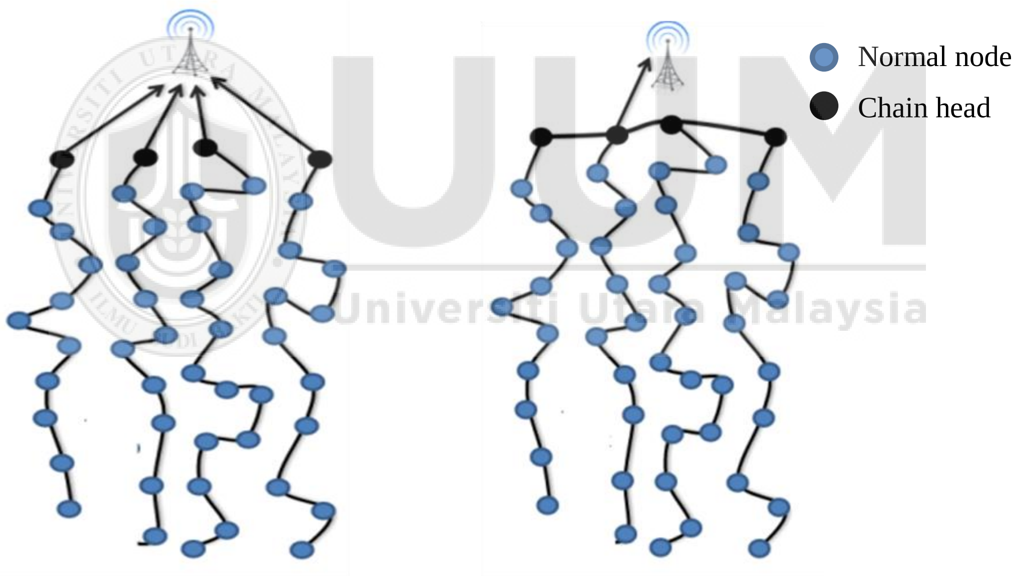


Figure 2.12. (a) Chain-Based1 Routing (b) Chain-Based2 Routing Protocol

The main advantage of both protocols comes from the multi chain concept. Reducing delay and saving nodes power as well as prolonging network lifetime are very important metrics in WSN. However, random deployments do not guarantee the distribution of nodes in sensing area, which means that some chains will have more nodes than others. Therefore, this can directly affect network performance. Moreover, single main head in an improved protocol (Chain-Based2) can cause bottleneck problems.

2.5.7 Clustered Chain based Power Aware Routing

Clustered Chain based Power Aware Routing (CCPAR) in [94] is an adaptive power-aware chain based hierarchical routing protocols. It assigns the cluster head functions to different nodes in order to distribute the power consumption in this role. CCPAR consists of many rounds, every round has three phases: first one is to divide sensing area into uniformly clusters, CH selection and CH chain construction. CCPAR assumes that the BS has global information about all nodes, so BS will divide the area into some clusters and choose one node from each cluster as CH based on its energy (except in very first round it is based on BS proximity). Also CH chain will compute BS and broadcast the chain information to all CHs (Figure 2.13) to start the next phase.

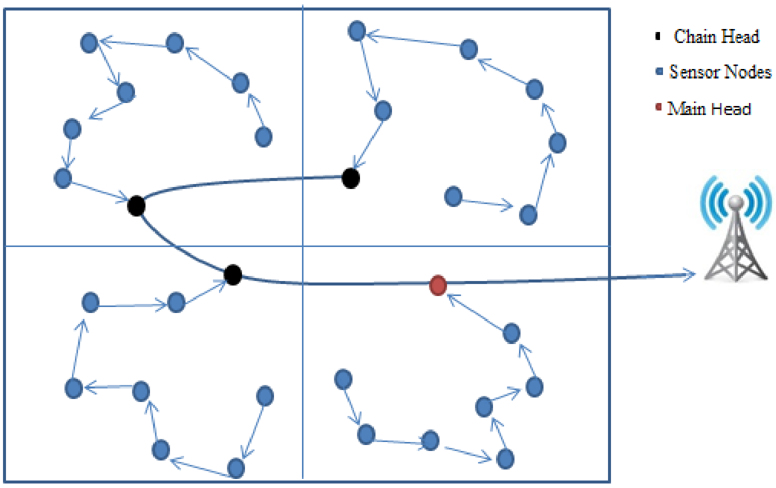


Figure 2.13. CCPAR Protocol

Second phase in CCPAR is to build the intra chain connection between ordinary nodes (ONs). This starts when CHs broadcast declarations message to all neighbor nodes to join its cluster, depending on signal strength of CHs. ONs will make decisions about which CHs to join by replying the declaration message to the selective CH1. Both declaration and reply message use CSMA as MAC protocol to avoid collision caused by all nodes transmitting in the same time.

When CH gets all nodes' response in its cluster, it will compute the intra connection chain between nodes then broadcast this chain to all non-cluster heads (ONs). After chain construction is done, CH broadcast a TDMA schedule depending on the number of nodes in this cluster. All nodes will send its data based on its time in TDMA to the closest neighbor.

Third phase is data transferring from all nodes to the BS. MIN threshold, MAX threshold, and change factor (CF) are three factors used by CCPAR protocol to control data transmitions. Every node senses the data and checks it when it is less than MIN value, this data will not be sent to the neighbor (ignore data). Sensing data between MIN and MAX with equal or greater than CF will be sent to the next hop and CH will forward it to the BS. Furthermore, when sensing data is greater than MAX value, node sends data directly to its CH without using multi-hop method then CH forward it directly to BS ignoring all chain-based nodes level.

CCPAR is beneficial for time sensitive applications when MAX condition is needed in every node. This factor is just like the priority factor or argent factor which tells other nodes that this data is urgent in order to deliver it without delay caused by long chain. CCPAR put MIN and CF to reduce data aggregation and fusing processing to reduce energy consumption by transmitting unnecessary data in the network. CCPAR uses first order radio model as a network model and this is compatible with chain concept because it uses the distance as a main factor to compute the energy consumption in each sender and receiver side.

However, CCPAR has drawbacks during broadcasting messages by BS and CHs, more overhead, time and energy are needed to reach all protocol requirements. Moreover, even though MIN and CF reduce data transfer to BS, it can consume more energy and delay in computational processes as usual in other protocols. Author did not clearly discuss the chain construction in intra and inter connection method and therefore long distance may occur among CHs. Finally, random deployment used in CCPAR does not give guarantee to uniformly deployment, so, many regions may not be covered by these nodes and on the other side many regions may have lots of closest nodes.

2.5.8 Energy Efficient Chain-Based Routing Protocol

Energy Efficient Chain-Based Routing Protocol (EECB) in [95] is an improvement on PEGASIS. It avoids a long link (LL) between nodes by adopting distance threshold on the chain. EECB has three phases, first phase is a chain construction phase: in this phase EECB employs greedy algorithm to construct the main chain through putting one condition that is distance threshold ($D_{threshold}$) to prevent the negative effect of long link among some nodes. Chain construction happens in first of every round; chain starts from furthest nodes in the network and every link is compared with distance threshold factor. When it is equal or smaller then this node successfully joins the chain and, if not, the node will be connected to the nearest node only (as a tree topology) Figure 2.14a,b shows the difference between chain construction by PEGASIS and EECB for same nodes deployment.

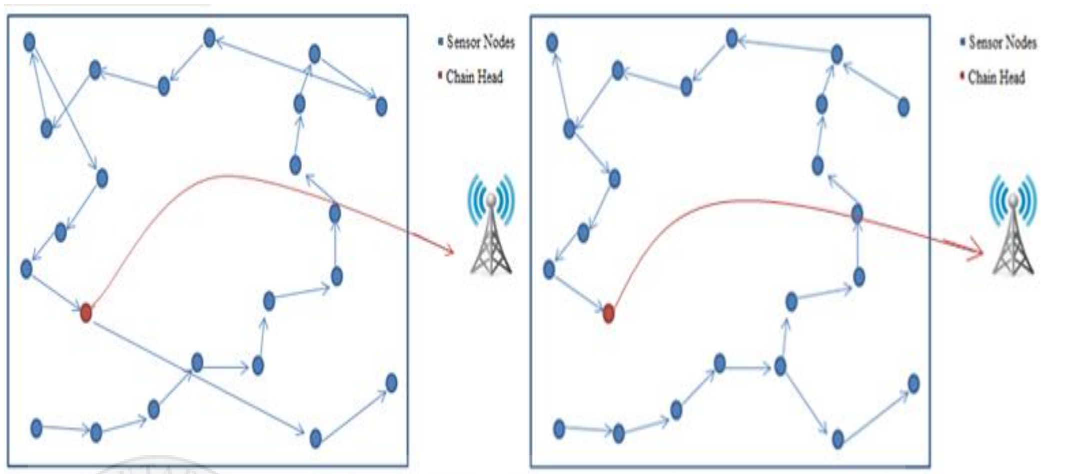


Figure 2.14. (a) Chain by PEGASIS (b) Chain by EECB

Second phase is for leader selection; EECB has distance and energy to choose the suitable chain leader. Therefore, round Equation 2.4 is used to calculate the Q*i* factor and Equation 2.3 is used to compute the d*i*.

$$d_i^2 = (X_i - X_{BS})^2 + (Y_i - Y_{BS})^2 \quad (2.3)$$

$$Q_i = {E_{residual-i}}/{d_i} \quad (2.4)$$

BS will compute Q factor in every round then the node that has larger value for Q will become a chain head of the round. Third phase is to transfer data; in this phase EECB uses simple control token passing approach to control data transfer from all nodes to the chain head and BS. EECB performs data fusing in every node like

PEGASIS to reduce data redundancy and minimize the amount of data transfer to the BS.

The advantages of EECB include avoiding LL by distance threshold among nodes. This can significantly save energy dissipation caused by long connection because EECB uses first order network model like PEGASIS and the distance is very important factor in sending and receiving data. Furthermore, EECB uses distance and residual energy when selecting chain head, therefore this can save energy and prolong network lifetime.

However, EECB only considers distance and as compared to its threshold, ignores the energy when connecting to the next hop. This makes nodes, that have low energy, join the chain and some nodes will be disconnected at any time during this round and data to be lost.

2.5.9 Grid-PEGASIS

Grid-PEGASIS scheme in [87] is improved on PEGASIS protocol in terms of energy efficient and energy balancing. It is created to prevent the long hop caused by greedy algorithm through dividing sensing area into small grid areas. This scheme has many assumptions before starting which are (1) all nodes in the network and BS are stationary, (2) the sensing area is divided into small grids and every grid has unique ID, (3) each node has unique ID and knows its Grid ID, (4) all nodes send data periodically and they are homogeneous.

Grid-PEAGASIS divides area into small grids and every grid has nodes that are assigned as start node and end node in every grid. The role of start node is to connect next grid to the end node. Furthermore, Grid-PEGASIS has been applied in three types of topologies including Deterministic Topology (DT), Intra-Grid random (IGR) and random deployment. In DT, the nodes will be installed in specific predetermined location whereas in IGR sensing area will be divided into specific grids and nodes that are randomly deployed in each grid and so on. Figure 2.15a,b shows both DT and IGR based on Grid-PEGASIS protocol.

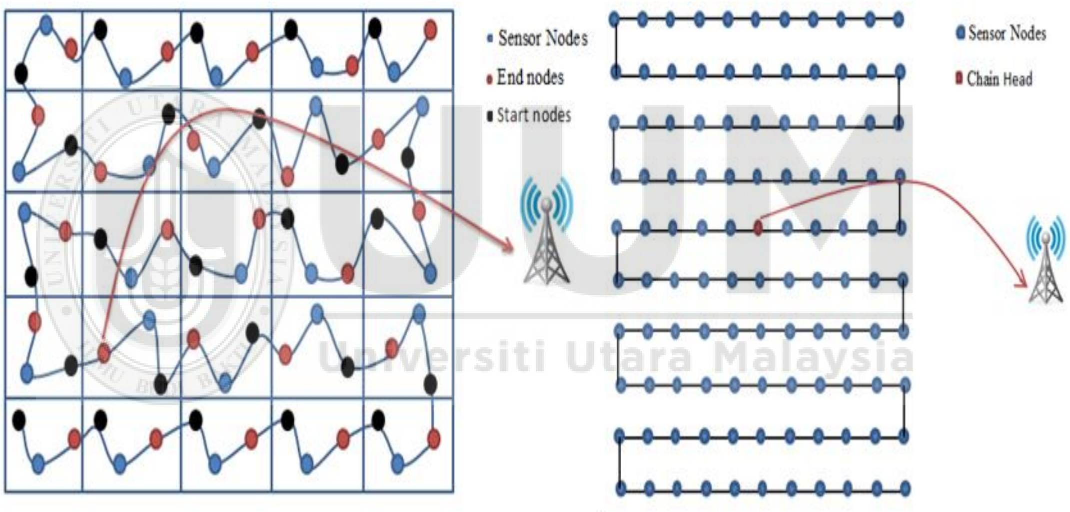


Figure 2.15. Grid-PEGASIS Protocol (a) DT and (b) IGR

In each grid, chain will be constructed using greedy algorithm and chain head will be selected in the same way in PEGASIS applying Equation 2.5 (since *i* is current round and *N* is the number of nodes in this network). This is important to make sure the random location for CH in the topology and this can assist to balance the power consumption in CH.

$$CH = i \; mod \; N \tag{2.5}$$

The advantage of this protocol is to avoid long hop link happen in some nodes with PEGASIS. However, main disadvantage of Grid-PEGASIS protocol comes from single chain construction through a lot of nodes, delay and redundant data cannot be avoided in these protocols during long links. Methodology to select start and end nodes is not explained. Furthermore, random selection of chain head will cause many problems for these nodes in terms of distance between base station, chain head and energy. Two important factors are not considered by this protocol. Finally, single chain head will cause bottleneck problem so CH nodes will spend its energy very quickly than others.

2.5.10 Rotation PEGASIS Based Routing Protocol

Rotation PEGASIS Based Routing Protocol (RPB) in [96] combines the advantages of PEGASIS with GAF (Geographical Adaptive Fidelity) [97] in one protocol. RBP consists of three stages which are link establishment, leader selection and data transmission. In link establishment phase, distance threshold factor will control link construction. Link starts from the farthest node in the sensing area. Every node will check the distance with its neighbor with distance threshold. When the distance is more than distance threshold, the node will be connected directly by sending connection message request and waiting to receive conformation message. When the distance is less than or equal to distance threshold, the node will go to sleep mode in this round and wake up before next round comes and rotate this role with the neighbor node. Figure 2.16 shows chain built by RPB protocol using sleep nodes.

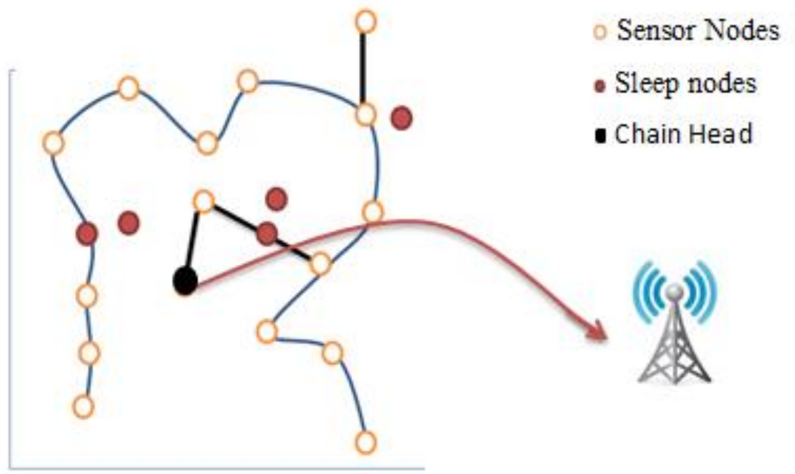


Figure 2.16. Chain Constructing by RPB Protocol

Second phase is chain leader selection. RPB selects leader node based on residual energy and distance with base station with two specific weights including w_1 and w_2 to control efficient selection of chain leader as shown in Equation 2.6.

$$Q_i = W_1 * E_i + W_2/d_{BS(i)} \qquad (2.6)$$

Where Q_i is comparative factor used by base station to select chain leader, *Ei* is the residual energy of the *i* node, d_{BS} is the distance between node with BS and W_1, W_2 are weighted variables to make sure the efficient selection of chain leader and $W_1+W_2=1$ and always $W_2 > W_1$ to give some priority for distance factor.

Third phase is Data Transmission phase. Every node will decrease its energy radio transmission to hear only closest neighbor node. RPB uses token mechanism to start data collection from all nodes. Token packets are very small, and take very few energy to process and transmit a long chain member. Like PEGASIS, each node receives data from its neighbor and fuses with its data and forward the fused data to the next hop until it reaches the chain head, then chain head will fuse all network data and deliver it to the BS in the end of each round.

Some nodes are very near to each other because they are randomly deployed. RPB is beneficial when making distance threshold and using sleep mode for the nodes to save their energy in this round. Another advantage of RPB is when the chain head is selected through considering both residual energy and distance with BS and put some priority for distance.

However, RPB has disadvantages as well. When it loses the sleeper coverage range along with round time, an overhead will be caused by selected sleeper nodes. Also these authors did not provide enough explanation regarding the methodology of calculating distance threshold. On the other hand, single chain head causes a bottleneck problem when only one node in the network is responsible for delivering all network data to the base station.

2.5.11 An Energy Efficient Cluster-Chain Based Routing Protocol

The aims of Energy Efficient Cluster-Chain Based Routing Protocol (ECCP) [98] are to balance energy consumption among all sensor nodes in the network, prolong network lifetime and power conservation to make WSN more stable and robustness. ECCP makes strong assumptions regarding sensors before starting the first round which are:

1- BS and sensors are stationary after deployment.

2- All sensors find their location using GPS.

3- Sensor nodes in the network have homogenous capability and have the same initial energy.

4- Finally, energy consumption to send data from X node to Y node is the same in reverse direction.

ECCP consists of three main phases which are: clustering phase, chain formation phase, and data transmission phase. In cluster phase, cluster head is selected first and all nodes send their information (residual energy and location) to all neighbors in specific *r* radio range (20m) and node that has the highest weight *Wi* will become the cluster head for this round. *Wi* can be calculated using Equation 2.7, which is as follows:

$$W_i = RE_i * \sum_{j=1}^{no.of\ neighbor} 1/d^2(v_i, v_j) \quad (2.7)$$

Where RE_i is the residual energy, d is the distance between node *i* and node *j*. the node which has the highest weight will be selected as CH and will send advertising message to all nodes in *r* range to invite them to join its cluster. Depending on the signal strength, sensor nodes will decide which CH will join. A high overhead during the clustering phase is applied and therefore cluster phase will not be performed in every round. Only when node dies, the CH sends message to the BS to inform it that sensor nodes need cluster phase in the next round, however, no node dies in the cluster, the cluster will only choose CH in every round based on residual energy in the member nodes.

Chain formation is the second phase in ECCP. The cluster node constructs the chain along all its cluster member nodes starting from the furthest node to the CH. The CH will create TDMA schedule to allocate time for every node to transmit its data. After that, chain formation among all CHs will be constructed by BS using greedy algorithm (same in PEGASIS) starting from the furthest CH in the network. Main leader node will be selected based on proximity from the BS. All data will be transferred along this chain until it reaches the BS. This process is demonstrated through Figure 2.17. After creation, they will transfer their data.

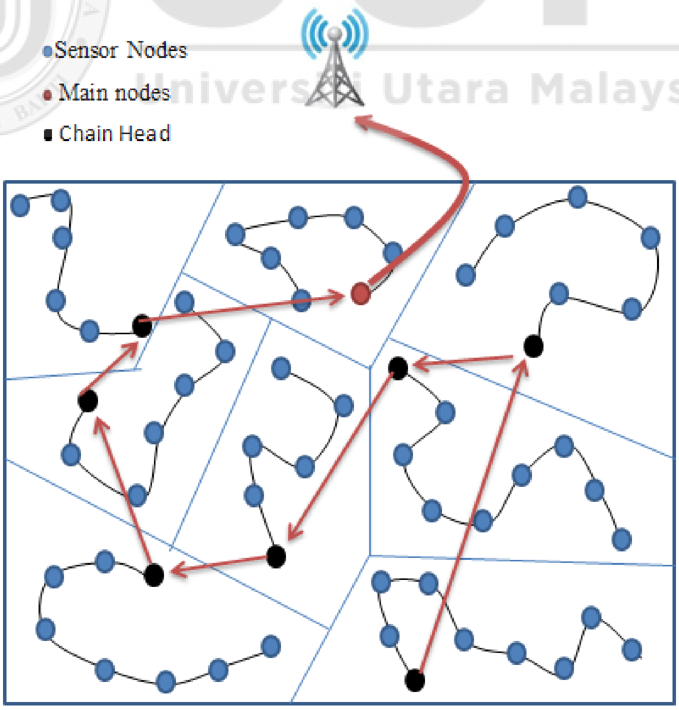


Figure 2.17. ECCP Routing Protocol

The last phase in ECCP protocol is data transmission phase. In this phase, token mechanism controls the transmission of data. Every member node in the cluster will receive data from previous node and fuse it with its data then send it to the next hop until it reaches the CH. Then, in the same way CHs will collect data through their chain and send it to the main leader node. This node is responsible for delivering all network data to the BS in the end of every round.

ECCP has advantages when it applies Equation 2.7, which is the summation of distance between nodes and residual energy. It is important to select CH but it is unnecessary for each node to broadcast its energy to the other node. While they will distribute the weight among all nodes, this weight is enough to make decision about CH and more overhead will be applied for unnecessary messages. Furthermore, choosing CH in the next round based on its energy will provide inefficient CH for the cluster.

Also, ECCP has problem when selecting the main head based on distance from the BS only. The main head may drain its energy more quickly than others. Moreover, greedy is not efficient when creating the chain in inter connection because of its behavior to select next hop based on linking distance only and ignoring residual energy for this decision. Finally, random deployment makes it difficult for protocol to balance the number of nodes in every cluster because of unpredictable positions of sensor nodes in the sensing area.

2.5.12 Improvement Energy-Efficient PEGASIS Based

IEEPB proposed in [99] is an improvement protocol on energy efficient PEGASIS based protocol (EEPB) in terms of chain construction and chain head selection. In order to avoid long line chain and to select efficient chain head based on residual energy and distance with BS, IEEPB is assumed to be the best protocol. Typically, IEEPB consists of three phases, the first one is chain construction phase. In this phase, BS will broadcast hello message to all nodes in the sensing area, thus all nodes will know their position or distance based on signal strength from BS. Chain starts from farthest node in the area; this node will explore the nearest node and will connect to it. IEEPB is based on threshold α and chain building. This phase is shown in Figure 2.18.

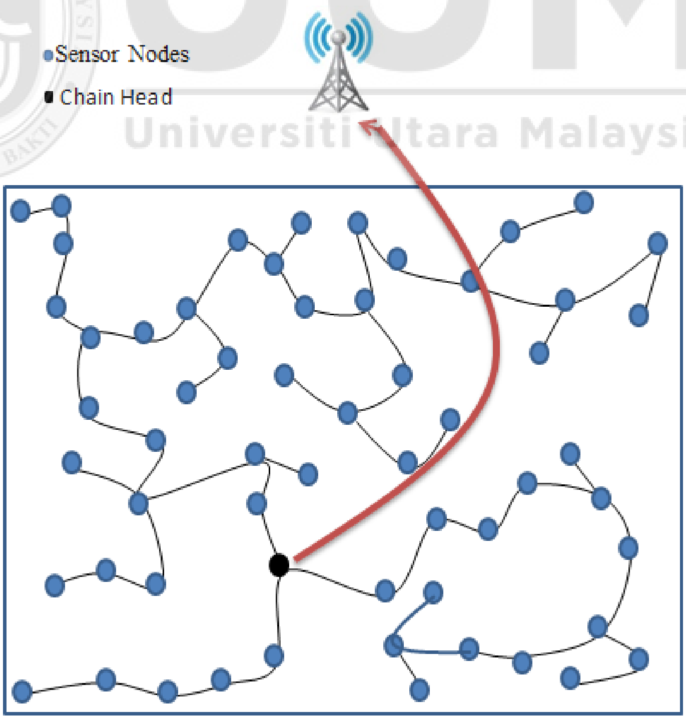


Figure 2.18. IEEPB Routing Protocol

Second phase is chain head (leader) selection and in this phase IEEPB uses weighting method to put some priority for distance or energy based on the following Equations: 2.8 and 2.9.

$$D_{bs} = {d_{BS}^4}/{d_{ave}^4} \tag{2.8}$$

$$E_p = {E_{inti}}/{E_{rem}} \tag{2.9}$$

Where D_{bs} is the ratio between distance from node i and BS with total average distance for all nodes with BS. E_p is energy ratio between initial energy for node *i* with its remaining energy. Both D_{bs} and E_p are used to calculate nodes weight W_i and this weight is used to assign chain head in IEEPB protocol using Equation 2.10.

$$W_i = w_1 * E_p + w_2 * D_{bs} \tag{2.10}$$

Where, $w_1+w_2=1$, w_1& w_2 are coefficient of weighting factor used to assign priority of energy or distance based on network requirements. Basically, $w_1 > w_2$ when the energy is more important and $w_1 < w_2$ when the distance has more priority than energy. As a result, node which has a minimum weight *w* will be chain head in this round and next stage will start.

Third phase in IEEPB protocol is for data collection. IEEPB uses token mechanism to control data collection from all nodes among chain. This protocol may have more than one end, thus TDMA mechanism is used to assign time slots for the end node. Then, data aggregation starts from the last node in the network; every node will send its data to the next hop in the chain. This node will fuse received data with its own data and forward it to the next until it reaches the chain head which is responsible for delivering all network data to BS.

IEEPB has main advantages when it avoids long link in the network and uses weight method to select chain head. However, IEEPB does not have designed method to select w_1 and w_2 and to assign the priority for distance or energy.

2.5.13 Chain Based Cluster Cooperation Protocol

The main objective of Chain Based Cluster Cooperation Protocol (CBCCP) [29] is to conserve the energy in communication to prolong the network lifetime. To achieve its CH election, it is made in each cluster and to make the protocol more reliable, re-election of CHs is accomplished when earlier CHs reached the threshold of energy level. Residual energy of nodes can be easily estimated by computing the energy used in sensing, processing and communication. To meet the objectives, CBCCP starts its processing by dividing the area into ten subareas (clusters for example) with dimensions of 200 m by 20 m. From each dimension one node is assigned the role of CH randomly. The subarea in the region of 0–200 m × 0–20 m is the first level cluster which has one CH to transmit the data to next level cluster (0–200 m × 21–40 m) and received by the node which acts as the cluster coordinator (CCO) for the first level cluster. It is forwarded to the next level CCO in the next cluster (0–200 m × 40–60 m). This process continues until the data is forwarded to the BS. Each cluster has one CH and varied number of CCOs. Number of CCOs depends on the number of clusters beneath the cluster in which CCOs are located. It is the responsibility of cluster to have one CCO for each cluster for the data of cluster lying below it. For example if there are seven clusters below one cluster then there will be seven CCOs in that cluster to handle the data of each cluster.

CBCCP protocol can make a kind of load balancing by dividing the network weight on CCO nodes till all network data reach the BS. However the first CH with CCO path suffers from excessive data from the first CH, therefore these nodes will deplete its energy faster than others. Second important thing is that when the CH is selected randomly, it may not be the suitable node (from energy or distance perspective) to be CH.

2.6 Chain Based Routing Protocols in Deterministic Deployment in WSN

The chain-based is considered as the best among all other energy efficient routing protocols in WSN [18], [92] and deterministic nodes deployment can reduce the node redundancy, minimize the network overall cost, prolong the network lifetime, reduce the complexity of data fusing and routing, and make the network topology more controllable [32], [34], [37].

Therefore, many protocols are used in chain-based routing approach with deterministic sensors' deployment in WSN to achieve efficient energy consumption during the network lifetime. Chain-Cluster based Mixed (CCM) [100], Chain-Chain Based Routing Protocol (CCBRP) [28], Two Stage Chain Routing Protocol (TSCP) [18], and Hamilton Energy-Efficient Routing Protocol (HEER) [101] are discussed in detail in the next sections in terms of their phases.

2.6.1 Chain Construction

In CCM protocol all sensor nodes are evenly deployed in the sensing area, thus two dimensional assigned name can be taken to every node as its id like *S(i,j)*, where *i* refers to the number of rows and *j* is the number of columns. Then, the chain will be constructed among all nodes in the same row (*for S(i,1), S(i,2), S(i,3), ….*), this means the number of rows is equal to the number of chains in this protocol. From every chain, one node is responsible for being a chain head and the chain head makes a cluster (one hop cluster) and the main head sends its data to the BS. Figure 2.19 shows the chain and the cluster built by CCM.

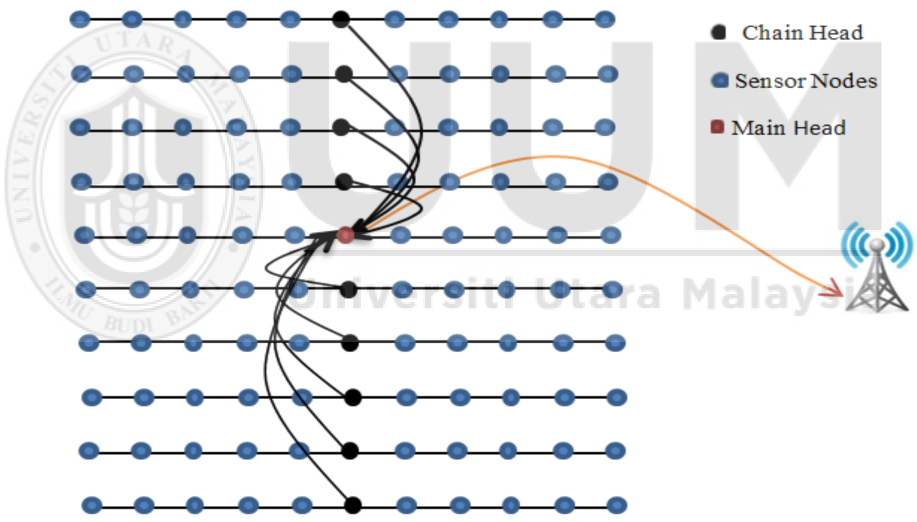


Figure 2.19. Chain and Cluster Formation in CCM

CCM can reduce the power consumption in intra connection by playing chain concept (every node will tune its power radio to hear two neighbors only), however, it conserves more energy when cluster approach is applied in inter connection and when head nodes are far away from each other.

CCBRP is also evenly distributed (deterministic deployment) for nodes in sensing area and construct its chain in every row depending on greedy algorithm to make sure every node will connect to the closest neighbor only (depending on distance only). Moreover, chain among all chain heads will be built using greedy algorithm and this is called main chain. Figure 2.20 shows the chain construction in CCBRP.

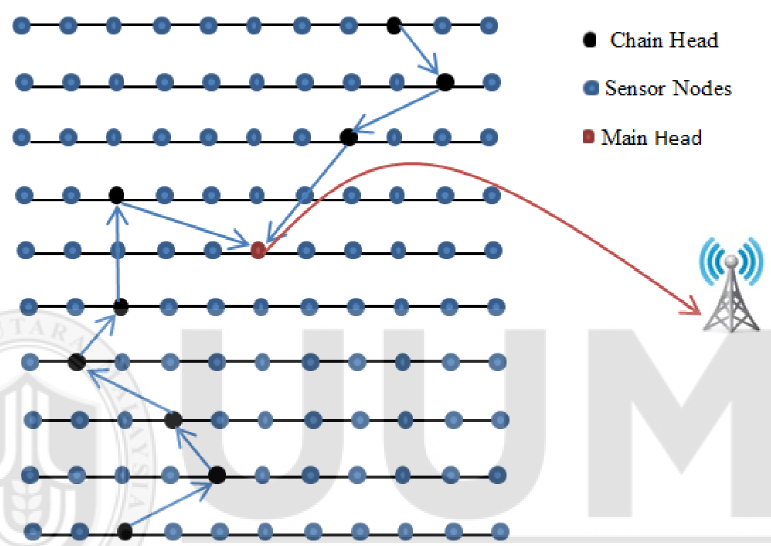


Figure 2.20. Chains Built by CCBRP Routing Protocol

CCBRP has several advantages over CCM when it uses Greedy algorithm to build its chain because CCM does not put any solution when one node dies and the way the previous node will connect to the next node during long distance. While in the CCBRP, Greedy is trying to choose the nearest next hop connection.

However, Greedy algorithm has two problems, one on the long distance in some links and another one when it chooses next hop based on its distance only and ignores the residual energy, so this behavior makes some nodes drain its energy more quickly than others.

On the other hand, TSCP takes advantage from both CCM and CCBRP when it is built in two stage chain. The first chain is horizontal and CCM has intra connection, where every node in the same row will connect to two neighbors only (that means the number of the horizontal chain is equal to the number of rows in the network). Second from CCBRP, it makes chain among all chain heads to reduce power consumption which is unlike what happens in CCM (CCM uses clustering method in inter connection). Figure 2.21 shows these two chains constructed by TSCP.

Figure 2.21. Chains Constructed by TSCP Routing Protocol

TSCP successfully reduces energy dissipation and balances sensor nodes during sequential moving of inter chain (vertical chain for chain heads). However, this does not clearly mention about nodes' death and how the network will deal with these issues. CCBRP uses greedy algorithm, which plays with distance parameter to decide for the next hop connection. Furthermore, TSCP protocol applies a new method in the network when nodes share their energy in vertical chain. Chain construction will depend on nodes that have maximum energy to build the main chain and this method really can affect the network performance when vertical nodes are far away from each other.

HEER Forming clusters like LEACH in the first round. Randomly selecting some nodes as CHs and the other nodes would join the cluster which is closest to their locations.

Step 1: Each round selects CHs according to node's residual energy. Therefore, node having more residual energy has more probability to become CHs.

Step 2: After forming clusters, next task is to find a Hamilton Path in the clusters. Finding Hamilton Path means that it only can use approximate algorithm to calculate it. The cluster members' relative location information can be gathered by CHs when forming chain and CHs use the information finding Hamilton Path by Greedy Algorithm.

Step 3: The end nodes start to transmit its own data to its neighbor who is closer to CH and the neighbor would aggregate its detected data and received data until reach the CH. After CH receives all non-CH nodes' data, it sends entire detected data in cluster to sink base. Next round would select a CH in Hamilton Path again and execute Step 3 again, for HEER protocol only needs to form chain one time in the whole lifetime so that the repeatedly forming clusters energy consumption can be saved comparing with LEACH and LEACH based protocols. The chain that connects all cluster members will then be established with a Greedy algorithm. According to only forming clusters for one time, clusters and each cluster members would be fixed. This is good for data collection though chain because all cluster members are fixed therefore the chain can be repeatedly used each round. This saves the energy to find chain each round and reduces delay of the WSN.

HEER successfully reducing the overhead by constructing the chain only one time for all rounds for the same CH. However, this way ignores the residual energy for nodes in the chains which will cause "weak node being in the mid of chain" and it is subject to failure during the transmission time.

2.6.2 Chain Head and Main Head Selection

Typically, there are two ways to select CH in WSN depending on the parameters that are used: deterministic way which depends on fixed parameters and adaptive way that depends on variable parameters like remaining energy (weight-based method) [4]. CCM has assigned chain head in each row (horizontal chains) sequentially for every round (node 1 will be chain head in first round and node 2 will be chain head in the second round and so on). Moreover CCM will choose the main head based on residual energy in chain heads for which nodes have the highest energy. It will then be the main head and will be responsible for delivering all network data to the sink (BS).

Therefore, choosing sequential method to select chain head can reduce overhead on the network and minimize energy dissipation in computation processing. However ignoring the nodes remaining energy and this will make some nodes that have little energy to become the chain heads and these nodes will drain their energy quickly, whereas, if these nodes die then the network will lose chain data in this round. As such, chain head is responsible for sending all chain data to the main head.

Moreover, CCM uses residual energy only when selecting the main head has critical cases. Especially when the main head is far away from the BS, some chain heads have little energy but with very good position according to the BS. In these cases this node (main node) will spend its energy to deliver all network data to the sink and may die earlier than others.

While, CCBRP elects CH in every row randomly, Greedy algorithm is used to create link between them. CCBRP will select the main head randomly. This random selection is considered to be not efficient way for selecting CH because there are some nodes that will select CH despite it has little energy or its position is far away from other CHs or it has already played role as CH in the previous rounds. This issue will apply not fair rule based on all nodes in the chains. Main head in CCBRP is also suffering from random selection where unsuitable node may be elected to be main head in terms of residual energy, position from BS and the number of times that is selected as a main head.

In TSCP, chain heads will be selected by sequential way like CCM, for round1 first node in the chain will be chosen as the chain head in every row (horizontal chains), thus vertical chain heads will construct vertical chain and the chain head that has maximum residual energy will be the main head in this round.

In HEER design, all nodes in a cluster are chained on a Hamilton Path, which leads to think that those nodes can simply act as the cluster head that in turn to be more energy efficient. The total weight (distance) on Hamilton Path does not change and therefore no matter which node on the path is acting as the CH, the weight (distance) for collecting all data inside the cluster remains the same. Moreover, CH changing will occur after operating for a pre-set round time. The sensor node has more residual power more likely to be the CH. In this case, the nodes in a cluster will have similar power consumption, which achieves a fairer and more even power consumption distribution that will prolong the lifetime of the cluster.

As mentioned above, the sequential method has critical drawbacks when ignoring the remaining energy to select chain head. But TSCP will put another way to select CH when the network nodes drain their energy by choosing the chain head depending on the maximum energy for all nodes in the same row. However, this way will add more drawbacks to TSCP because vertical chain will be affected by long chain if chain heads are far from each other and this will make nodes spend their energy more quickly than the first way (sequential way). Moreover, for main head in TSCP, it is not enough to consider energy only for selection. Distance from base station is very important factor for the main head selection because distance d^2 will be increased by long distance and d^2 is the main factor in energy consumption (see Equation 2.14).

Additionally, single main node in all of these protocols causes a bottleneck problem since one node only plays as the role of gateway for network. This research takes Bottleneck problem from power consumption perspective not from congestion side because all network's data must be delivered to the BS by this node (main node) and as a result main node will drain its energy very quickly.

2.6.3 Next Hop Selection

Intra-connection in CCM, CCBRP and TSCP are the same, therefore connection starts from the first node in the row. This node will select the next hop only by distance and this connection will be repeated sequentially (for example node *S(i,1)* will be connected to its neighbor *S(i,2)* and so on). This type of choosing CH does not have flexibility for any change in the network. Therefore, if any node dies, for example, node *S(i,2I)*, it will make *S(i,1)* connection to *S(i,3)* directly though *S(i+1,1)* which is nearer than others. Greedy algorithm uses distance only to select next hop connection and this is considered inefficient method because some nodes are not suitable to be in the chain due to their low energy. While, the next hop in HEER protocol depending on the CH position and it applies the Greedy algorithm between CHs, this again will depend on distance between nodes and therefore ignores the node's energy.

Both CCM and CCBRP use chain head to send message to every end node in the chain in order to inform them to start sending data to their neighbors. This neighbor will fuse (aggregate) receiving data with its data and then forward to the next hop. Simple way is used in TSCP to send nodes data. Every node senses data and fuses it with received data then transmits it to the next hop. TSCP way is simple but it ignores data collisions without any arrangement for data sending.

2.7 Comparative Routing Protocols Table

In this section, comprehensive comparative Table 2.1 is presented to complete all idea on the chain based routing protocols in WSN in terms of protocols name, year, intra and inter connection, CH selection, node deployment and type, performance metrics, and advantages and disadvantages.

Table 2.1

Comparative Table for Routing Protocols in WSN

Protocol	Year	Cluster, Chain or Hybrid	Chain head/main head	CH /main head election method	Nodes Deployment & types	Chain Construction / Next hop method	Advantages	Disadvantages
LEACH [10]	2000	Cluster	Exist/Not Exist	determined a priori with threshold	Randomly Homogenous	-	1. Energy consumption by CH will be equally distributed. 2. Using TDMA as MAC protocol and this prevents clusters from unnecessary collisions. 3. Normal nodes not need to directly connect with the BS. 4. Less Delay according to single hop applied	1. Link between CHs and BS is long. 2. CHs selection not consider the energy 3. The dynamic cluster construction in every round adds extra overhead. 4. Data fusing occur in CH only. 5. More energy conservation according to single hop connection.
EE-LEACH [84]	2015	Cluster	Exist/Not Exist	based on the function of spatial density	Randomly Homogenous	-	1. Reduce the end-to-end delay, 2. Increase packet delivery ratio 3. Reduce the energy consumption	1. Select CH based on the function of spatial density and ignoring residual energy. 2. Select cluster member by energy only and ignoring the distance between nodes
PEGASIS [27]	2001	Chain	Exist/Not Exist	Using MOD method /none	Randomly Homogenous	Greedy algorithm	1. Reduce the clustering overhead by chain method. 2. Reduce power consumption 3. Reduce the amount of data	1. Assume that all nodes can directly be connected with BS 2. Use only distance to selected next hop by greedy 3. It is not suitable for deterministic

							transfer to BS	deployment 4. Single leader cause a bottleneck problem. 5.Delay and redundant data accrue in LL
CRBCC [90]	2009	Hybrid	Exist/ Exist	Top of chain/ Random	Randomly Homogenou s	Simulated Annealing algorithm	1. Reduce data delivery time from nodes to BS. 2. Minimize the power consumption in data aggregation by using global search algorithm (SA) instead of greedy in PEGASIS.	1. Chain leader election in the top of chains and these nodes will deplete its energy quickly than others 2. Randomly selection for the main head caused unlucky nodes selected twice or more than twice compared with others that never selected
REC+ [25]	2013	Hybrid	Exist/ Exist	Residual Energy divided by initial energy/ nearest CH to BS	Randomly Homogenou s	Divide network base Y-coordinator then one chain for every cluster	1. Use two thresholds to create cluster and select the CH, one for energy and the other for delay. 2. Use relay node method to reduce transmission power between CHs.	1. More overhead on the network during it three phases, 2. Assume all nodes can connect directly to the BS. to setup the first and second steps and this is not always can applicable in practical networks. 3. There is random deployment for nodes may be allocated in the specific area this is causes some of clusters have many nodes than other
BCBRP	2011	Chain	Exist/	By position/ Randomly from	Randomly	Divide network into	1. Reduce the power consumption by minimizing	1. Single chain caused more delay. 2. Randomly selecting for the main

[92]			Exist	largest sub-area	Homogenous	sub area then use spanning tree algorithm	the overall chain link with minimum Spanning tree algorithm instead of greedy 2. Avoid long link by dividing sensing area into sub-area.	head. 3. Single main head cause bottleneck problem in the network. 4. Randomly deployment is not always applicable with equal dividing area.
CHAIN-BASED1, 2 [93]	2013	Hybrid	Exist/Not Exist, Exist/ Exist	First node in the chain/ none, First node in the chain/ residual energy	Randomly Homogenous	Divide network base X-coordinator then every node connected with neighbor	1. Use multi chain concept to reduce delay and redundant data 2. Save nodes power. 3. Prolong network lifetime	1. Random deployment have not guarantee to evenly distributions for nodes in sensing area and that's mean some of chains have more nodes than others 2. Single main head in improvement protocol (Chain-Based2) can caused bottleneck problems. 3. Multi CHs without adaptive way to rotate role of CH reduced network lifetime
CCPAR [102]	2010	Hybrid	Exist/ Exist	Remaining energy and proximity from BS/ residual energy	Dividing sensing area and randomly in every sub-area	Divide network into sub area then build one chain for each	1. Suitable for time sensitive application and MAX condition in every node. 2. Put MIN and CF to reduce data aggregation and fuse processing to reduce energy consumption by transmitting unnecessary data in the	1. A lot of broadcasting messages by BS and CHs caused more overhead, time and energy needed to reach 2. Even MIN and CF are reducing data transfer to BS, this can take more energy and delay in computational processes as usual in

					Homogenous		network. 3. Use first order radio model as a network model which is compatible with chain concept	another protocols. 3. Method not mentioned for chain construction in intra and inter connections 4. Long distance may accrue between CHs.
EECB [95]	2010	Chain	Exist/ not-Exist	Remaining energy divided by distance / none	Random Homogenous	Greedy algorithm with threshold	1. Avoid LL by distance threshold between nodes, 2. Use distance and residual energy when selecting chain head.	1. Consider distance only and compared with its threshold, 2. Ignore the energy when connected with next hop.
GRID-PEGASIS [87]	2010	Chain	Exist/ Exist	Not mention/ Randomly position with mod method	Dividing sensing area and randomly in every sub-area Homogenous	Divide network into small grid area the apply Greedy in each	1. Avoid long next hop link happen in some nodes with PEGASIS.	1. Single chain construction through a lot of nodes 2. Delay and redundant data cannot avoid in these protocols 3. Methodology to select start and end nodes is not explained. 4. Randomly choosing for chain head 5. Finally single chain head will cause bottleneck problem.
RPB	2013	Chain	Exist/Not Exist	Energy & distance weighting	Randomly Homogenou	Build chain with distance threshold	1. Distance threshold for next hop connection 2. Use sleep mode for some nodes to save their energy.	1. lose the sleeper coverage range along round time and 2. Overhead caused by selection sleeper nodes.

[96]				method/ none	s	(node bellow threshold will going to sleep mode)	3. Select the chain head by considering both residual energy and distance with base station and put some priority for distance.	3. Methodology to calculate distance threshold is not clear.
ECCP [98]	2012	Hybrid	Exist/ Exist	Energy and neighbor distance weighting /shortest distance to BS	Randomly Homogenous	Divide network into clusters based on signal then apply Greedy algorithm in each cluster for chain construction	1. Use weighting method to select cluster head 2. Use data fusing in every node that will decrease message size.	1. More overhead will applied for unnecessary messages. 2. Choose CH base on its energy . 3. Select the main head depend on distance from base station only. 4. Greedy is not efficient when creating the chain in inter connection. 5. Randomly deployment makes difficult to balancing number of nodes in clusters.
IEEPB [99]	2011	Hybrid	Exist/Not Exist	Energy & distance weighting method/ none	Randomly Homogenous	Chain start from farthest node with threshold to avoid long link	1. Avoid long link in the network by using next hop connection threshold weighting 2. Use weighting method to select chain head.	1. Not designing method to select w1 and w2 and how to assign the priority to distance or energy. 2. Weighting method used in IEEPB is not efficient.

CBCCP [29]	2015	Hybrid	Exist/Not Exist	Randomly	Randomly Homogenous	Each row construct one chain and CH, depend on position	1. Energy balancing 2. Reducing the delay by apply multi hop concept	1. Energy consumption for first CH with CCO path 2. Random chose for CH 3. Increase number of CCO till BS will cause all nodes near BS energy consuming
CCM [100]	2010	Hybrid	Exist/ Exist	Sequential / highest Energy	Deterministic Homogenous	Each row construct one chain	1. Deterministic deployment with chain-based approach is applied. 2. Low overhead on the network. 3. Low delay in cluster part.	1. Conserved more energy in cluster part. 2. Use sequential CH selection. 3. Use residual Energy only to select main head. 4. Bottleneck problem in the main head node
CCBRP [28]	2011	Chain	Exist/ Exist	Randomly / Randomly	Deterministic Homogenous	Each row construct one/ CH apply Greedy	1. Deterministic deployment with chain-based approach is applied. 2. Use multi-level of chains. 3. Low overhead on the network.	1. Greedy ignoring energy when selected chain. 2. Long link maybe happen if CHs far each other. 2. Randomly choosing CH and main head make unreliable nodes assigned. 3. Bottleneck problem in the main head node.
TSCP [18]	2014	Chain	Exist/ Exist	Sequential / highest Energy	Deterministic Homogenou	Each row construct one/ CHs construct	1. Deterministic deployment with chain-based approach is applied. 2. Use multi-level of chains. 3. Low overhead on the	1. Sequential CH selection is inefficient way. 2. Choose main head depending on energy only. 3. Bottleneck problem in the main

					s	vertical chain	network. 4. Apply a type of energy balancing for all nodes.	head. 4. Unpredictable Long link in inter connection happen if using energy to selecting CH.
HEER [101]	2016	Hybrid	Exist/ Exist	Residual Energy	Deterministic/ Random Homogenous	Each node connect with neighbor only in one chain per cluster	1. Reduce the network overhead. 2. Reduce the power consumption for the first phase. 3. Calculate cluster size by payload	1. More process to calculate chain by Hamilton and sorting algorithm. 2. Energy remaining not enough to select the CH 3. Cluster/chain size fixed during the network lifetime ignoring nodes status

2.8 Summary

This chapter presented information on WSN and addressed the importance of node deployment in the sensing area. It highlighted routing as a crucial issue that directly affected the performance of WSN in context of energy consumption and prolong network lifetime. It also discussed chain based routing, which is one of the primary types of hierarchical approach and can reduce the power consumption by connecting every node with its neighbor only. Many protocols developed under chain-based routing concept such as PEGASIS in 2002 to HEER routing protocol in 2016. All these protocols focus on how to create chain (or cluster) in intra and inter connection manner. It is also intended to select the suitable chain head based on which parameters and transmitting data from sources (sensors nodes) to destination (base station). This in turn would help to yield benefits and advantages of deterministic deployments with chain concept which are used in CCM, CCBRP and TSCP routing protocols. Nevertheless, weaknesses of chain formation and chain head and main head selection were also noted in this chapter. Finally, comparative table was provided to show all the main characteristics of these protocols with major advantages and dis advantages.

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Introduction

This chapter provides the complete overview of the research methodology, which is used in this research. Design Research Methodology (DRM) [103] is selected to implement all the steps necessary for the proposed protocol. Therefore, this chapter starts with introduction in Section 3.1 then DRM methodology steps are discussed in Sections 3.2, 3.3, 3.4, 3.5 and 3.6. The performance evaluation metrics are discussed in details in Section 3.6.5. Subsequently, Chapter summary is presented in Section 3.7.

3.2 Design Research Methodology (DRM)

The main goal of this research is to design DCBRP as a chain based routing protocol, which works with deterministic nodes deployment in the sensing area with any deterministic deployment applications and has the grid topology. The DCBRP protocol consists of the following mechanisms: BCM mechanism for chain construction, CHS mechanism for chain head selection with suitable number of CHs, and NHC mechanism for next hop connection in each node levels. Then, these mechanisms are combined with necessary functions, data aggregation model and first order radio model for evaluation purposes.

The DCBRP routing protocol aims to prolong network lifetime, reduce power consumption and reduce the delay in routing layer for WSN with deterministic deployment using chain based concept. Choosing suitable research methodology approach is intended to realize this research successfully in pursuing all the necessary processes to meet with the research objectives.

The DRM research methodology has four stages (1) Research Clarification (RC), (2) Descriptive Study-I (DS-I), (3) Perspective Study (PS), and (4) Descriptive Study-II (DS-II). Figure 3.1 illustrates these stages and relationships between them with processes and outputs of every stage.

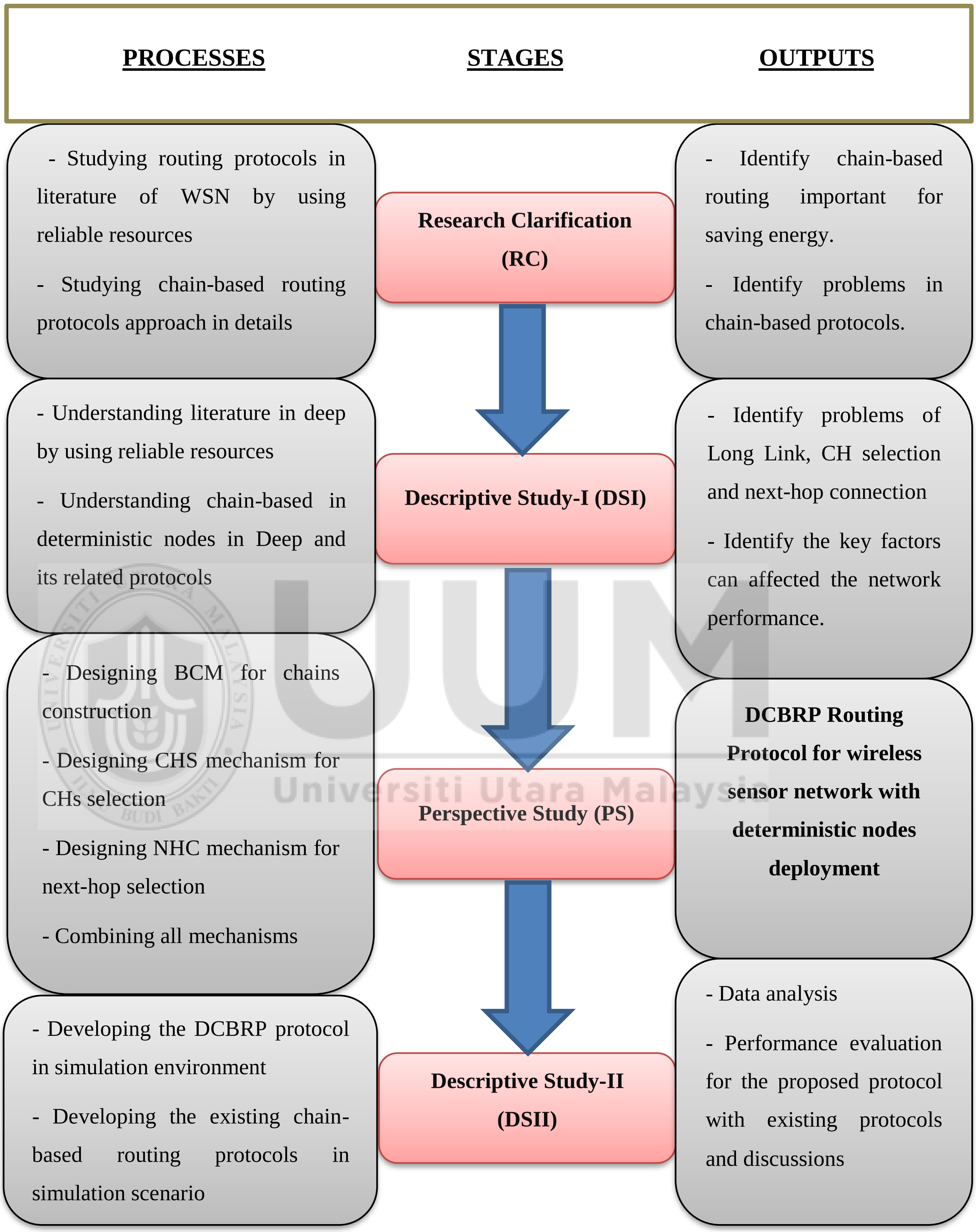


Figure 3.1. DRM Research Methodology Stages

3.3 Research Clarification (RC)

The RC describes the discovering of the wireless sensor network area in the literature, and presents the importance of the effectiveness of routing protocols on the performance of the whole network. In addition, understanding the chain based routing protocol in WSN and identifying the important characteristics of this approach and highlighting the main advantages and disadvantages comparing with other approach such as cluster-based are also covered in this stage. Moreover, Figure 3.2 presents the main steps of RC in this research beginning with the identification of the overall topics for routing protocols to the establishment of the research plan.

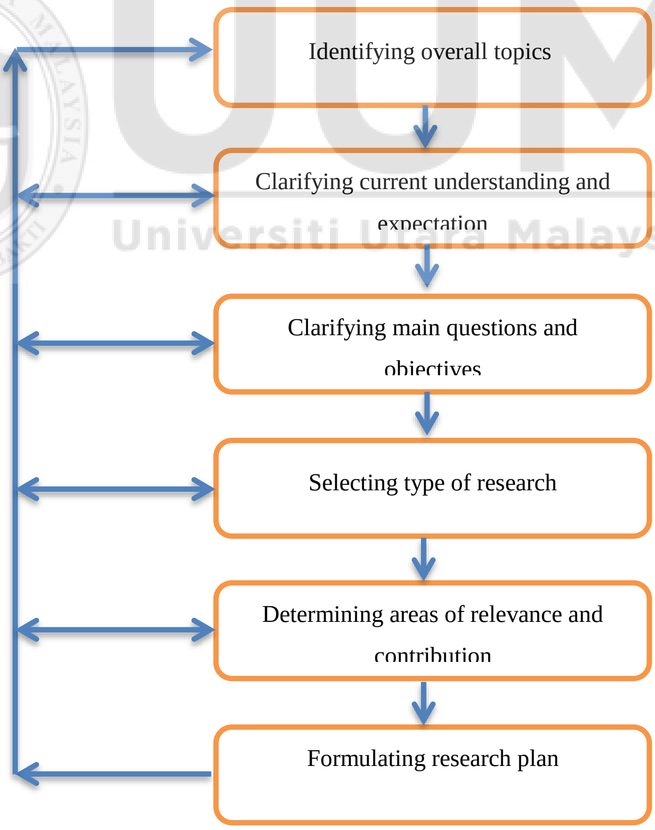


Figure 3.2. Main Steps in RC Stage

3.4 Descriptive Study (DS-I)

This section is intended to present the research in a holistic way. It focuses on the relation between deterministic nodes deployment and chain-based routing protocols. It helps to understand the chain-based protocols in deterministic nodes deployment and identifying the gaps within the whole protocols in the area of the current work. Furthermore, within DS-1 stage, this research identifies the important factors that can affect these problems. For example, the number of columns and rows the parameter that should be used to select chain heads in weight-based method. The parameters that should be used to select next-hop connection in each node in the network are important because this type of routing protocols have two different main tasks: First for creating topology and another one for assigning tasks to all devices [104].

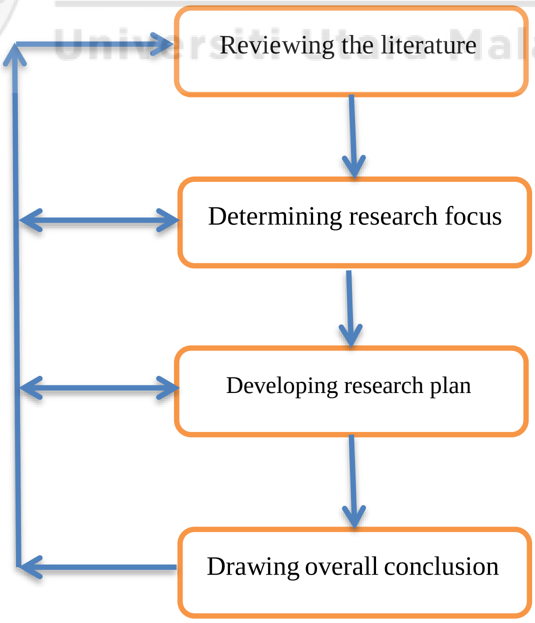


Figure 3.3. Main Steps for DS-I

Figure 3.3 illustrates the main steps for this stage beginning with reviewing the reliable literature collected from resources starts with the most trusted search engines and data bases such as Web of science, Scopus, Google scholar, ScienceDirect, IEEEexplorer, ACM and SpringerLink. The last step is drawing overall conclusion for this research by identifying the key factors that may affect the performance of chain-based routing protocols in WSN which are chain long, CH selection, next hop connection, distance and energy status.

Figure 3.4 shows the conceptual model of DCBRP protocol and the sequence of its mechanism working as a phase in the network lifetime, and its interaction with other important parts until all network nodes die.

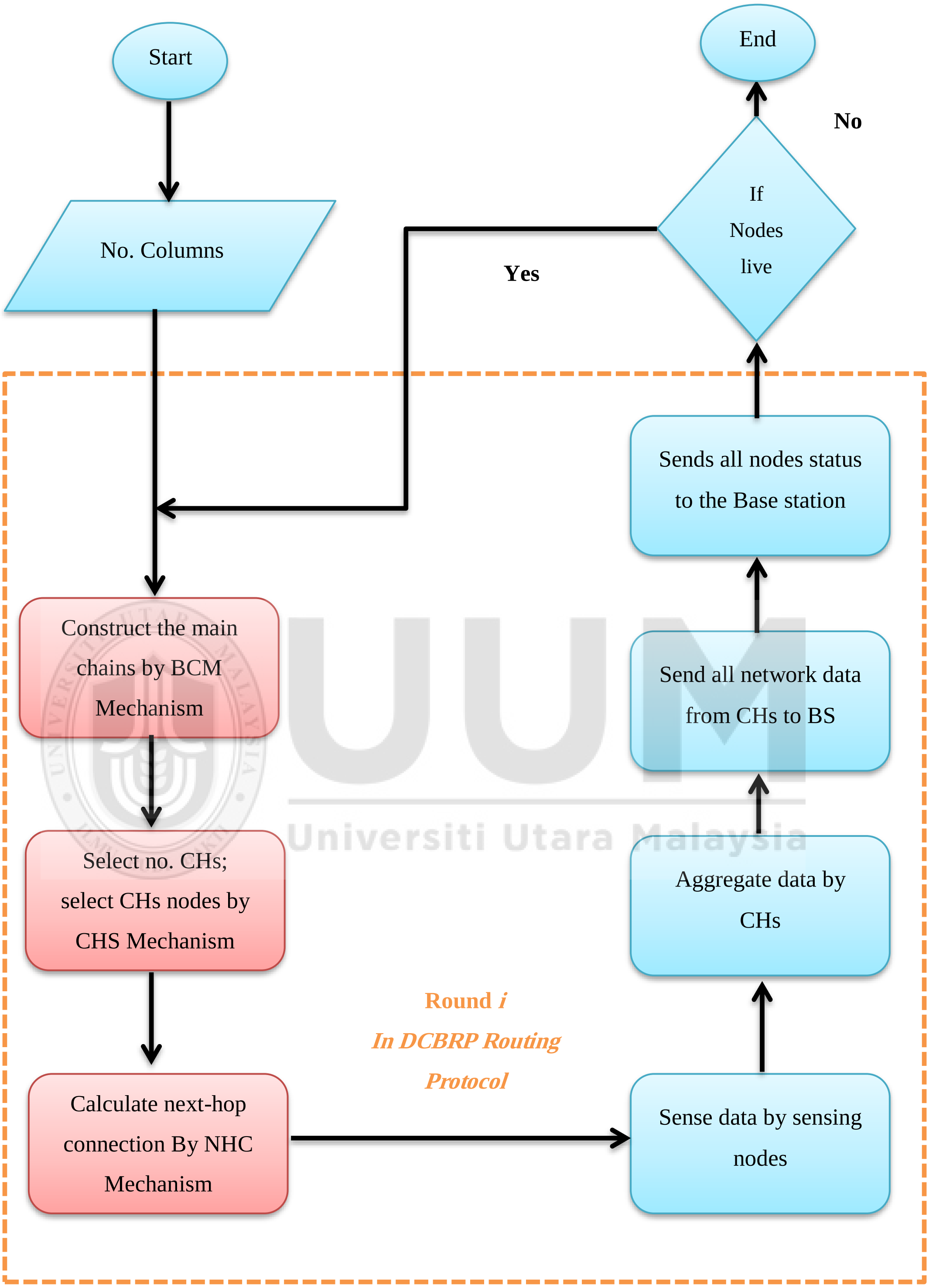


Figure 3.4. Conceptual Model of DCBRP Routing Protocol

3.5 Perspective Study (PS)

The PS stage is considered as the main stage in DRM [103] because it includes designing DCBRP routing protocol using all its proposed mechanisms:

a- BCM mechanism for multi chains construction;

b- CHS mechanism for chain heads' selection and choosing proper number of chain heads in all networks; and

c- NHC mechanism for the next hop connections.

All these mechanisms combine with other existing mechanisms such as data aggregation and deterministic nodes deployment mechanism using first order radio network modelling for energy consumption.

The second sub-stage in PS is to implement all these mechanisms in NS3, a network simulator and set the necessary scenario parameters in order to become ready for validation and verification steps, and to match simulation configuration of previous existing protocols to make it more reliable and achieve better results.

In addition, it is also important to define some of the assumptions before presenting any proposed protocol [14], therefore, in the very first round of the network, the DCBRP routing protocol has some assumptions as follows:

a- The BS has global knowledge about the number of nodes' columns and the number of rows as well as the total number of nodes in the network.

b- All nodes are homogenous and they can play the same role in the network, which are sensing, relay the previous data or chain head.

c- All nodes have adjustable radio power signals to make sure they can connect with close neighbor only with low power consumption and apply the chain approach concept;

d- All nodes and base station have fixed position (stationary) [105], and each node has unique ID, known as (x,y) coordinators (for example N10 in (X,Y) position);

e- Symmetric channel used in this research means that the needed energy for transmission from A to B is the same as the required energy from B to A; and

f- For nodes deployment in the sensing area, deterministic deployment way is used to distribute the sensor nodes with equal distance between them. The distance between nodes in installation manner is constant, and determined as d for all distance parameters in any equations in this research for more controllable purpose.

The network lifetime consists of the number of rounds, which relates to the period of time needed by the network to collect all nodes' data and deliver them to the BS in the end of the round (one packet from each node). The proposed protocol has four phases to complete its lifetime and to repeate periodically in every round, which include the chain construction phase, chain heads' selection phase, next-hop selection phase, and data collection phase.

3.5.1 Phase 1: Chain Construction

In this phase, the overall chains are calculated by the base station based on important criteria such as the number of columns and rows for nodes in the sensing area, and the distance between vertical nodes. The BS can compute the main chain and broadcast the chain by achieving the following three steps:

1- Calculating the number of clusters in the network: BS divides the network into specific number of clusters. Every cluster has three columns as maximum and two columns as minimum. The three and two columns for maximum and minimum are to ensure that every node has more than one option to select the next-hop connection, apply energy balancing in the nodes cluster, and avoid data lost in single chain construction because in single chain any intermediate node dying will cause all previous nodes to lose data.

2- Calculating the number of columns in each cluster: from the first step of this phase, the BS knows how many clusters are needed. Therefore, in this step network needs to know the number of columns in each cluster in order to assign the specific column to the specific cluster (which is three or two in each cluster).

3- Connecting horizontal nodes in chain form, i.e., every row in each cluster has two or three nodes only. The intermediate nodes for every cluster that has three columns will construct vertical main chain in this cluster. Choosing either right or left vertical nodes will construct vertical chain for the cluster, which has two columns that will be selected at random.

Figure 3.5 shows chains that are constructed by the first phase in the proposed protocol for 120 nodes that have deterministic deployment in 120X100 sensing area with d=10m as distance between nodes.

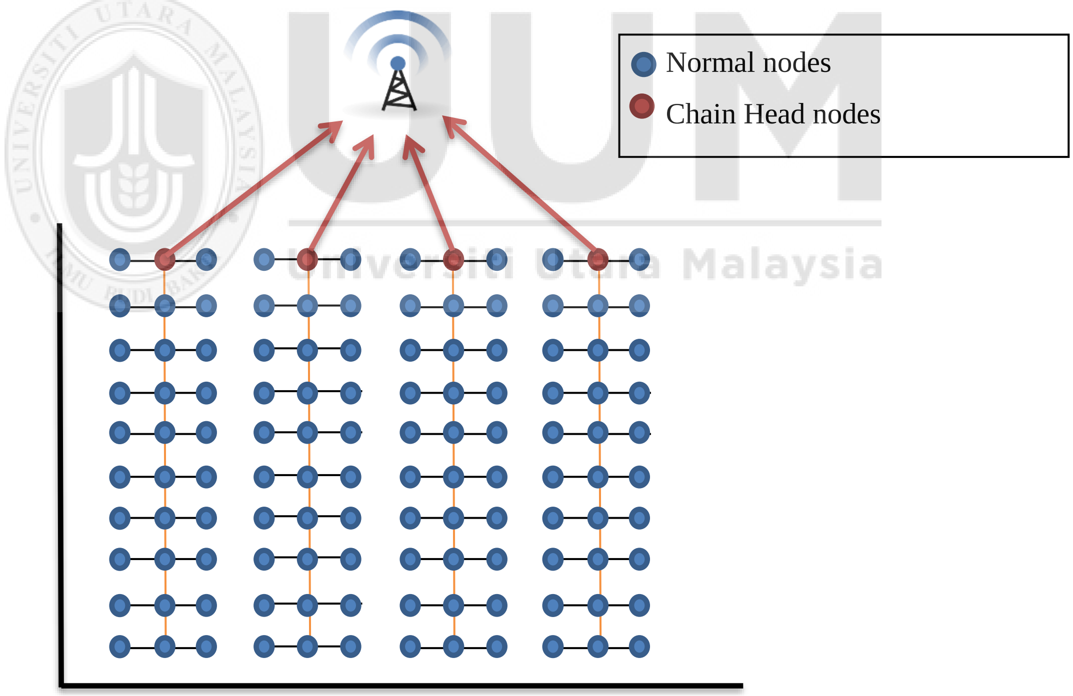


Figure 3.5. Chains Constructed by First Phase in the Proposed Protocol

Furthermore, to achieve the first phase completely, the following flowchart in Figure 3.6 will be executed to construct the whole topology chains in any number of nodes in the network.

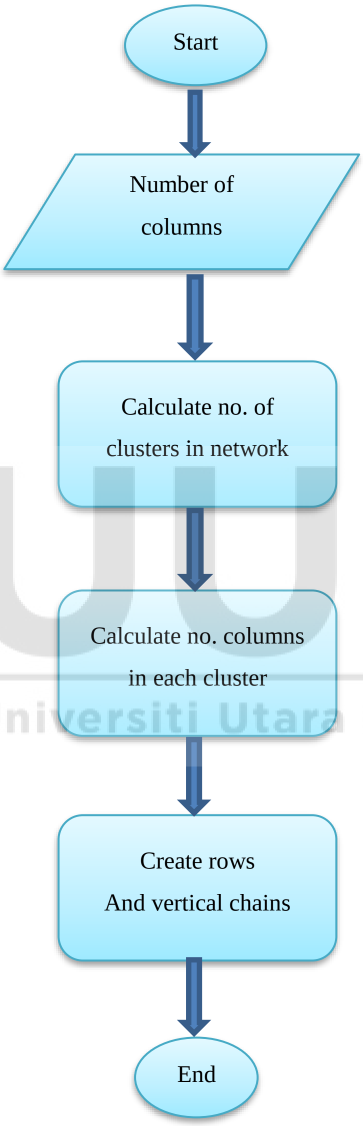


Figure 3.6. Chain Construction Flowcharts

3.5.2 Phase 2: Chain Heads Selection and Numbers

Chain heads are nodes selected by BS for sensing data collection from the normal nodes in the network and delivering them to the base station or to the main heads, and finally to the base station. This phase has two important steps, which can be explained below:

1- To calculate the number of chain heads in the network. From the first time the number of chain heads is equal to the number of clusters in the network to make sure that every cluster has one chain head. More than one CHs is important for energy balancing and keep the network out of bottleneck problem.

2- To calculate which nodes will be the chain heads for the next round. These chain heads will be selected based on the ratio between their energy consumption that is expected to spend if it is selected over remaining energy. Therefore, by using this method the nodes that have lower value of ratio will be selected to ensure that the best nodes will be chosen to play as chain head with lower energy consumption as possible. Phase 2 is represented in Figure 3.7.

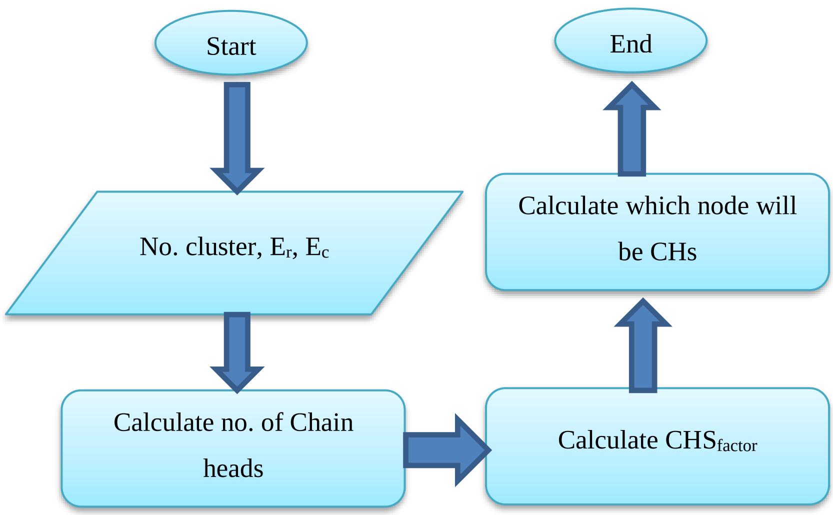


Figure 3.7. Phase 2 Flowchart to Select no. of CH and CH Selection

3.5.3 Phase 3: Next Hop Selection

In this phase, the BS needs to broadcast the next-hop connection for each node in vertical chains in each cluster. This phase is very important to recalculate the vertical chains. These decisions are dependent on the node energy and the distance with the next level. This procedure can be done through the following steps:

1- At the end of round, each node will send its energy to chain head and consequently, the chain heads will forward all nodes' status to the BS.

2- The BS will calculate weight factor for each nodes. The node that has the higher weight factor will be chosen as next hop for this node in the vertical chains. Weight factor calculation is based on the remaining energy and distance among nodes to reduce the energy balancing problem caused by multi hop [106].

3- The BS will broadcast updated vertical chains to all nodes in the network and the chain construction will commence from the farthest nodes.

4- This phase can overcome Greedy algorithm behavior problem because the Greedy depends only on distance to make decision for next hop connection. Furthermore, nodes do not need to spend their energy for unnecessary computation operation. The BS can perform this for all nodes because it has unlimited power resources. Figure 3.8 shows the flowchart of phase 3 for next hop selection.

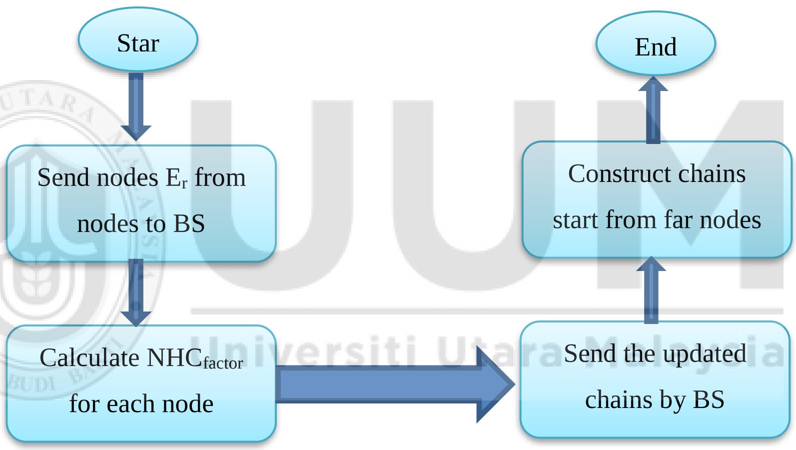


Figure 3.8. Phase 3 Next Hop Selection Flowchart

3.5.4 Radio Model for Energy Consumption

This research adopted the First Order Radio Model as energy model which is the same radio model used in [10], [27], [106]–[109]. In this model, the energy needed for running transmitting or receiving circuit is $E_{elec} = 50\ nJ/bit$ and the energy that is required by the transmitting amplifier is $E_{amp} = 100\ pJ/bit/m^2$. So, Equation 3.1 is used to transmit k-bit from any node to other with d distance between them and Equation 3.2 is to receive k-bit in any node.

For Transmit *k*-bit

$$E_{TX}(k,d) = E_{TX-elec(k)} + E_{TX-amp}(k,d) \quad (3.1)$$

$$E_{TX}\,(k,d) = E_{elec} * k + E_{amp} * k * d^2$$

For Receive *k*-bit

$$E_{Rx}(k) = E_{Rx-elec}(k) \quad (3.2)$$

$$E_{Rx}(k) = E_{elec} * k$$

Where E_{TX} is energy for transmission, E_{elec} is energy to run transmitting circuit for 1 bit, E_{amp} is energy required for amplifier for 1 bit for m^2, k is number of bit and E_{Rx} is energy required to receive k bits. Figure 3.9 shows the basic elements of the first order radio model [110].

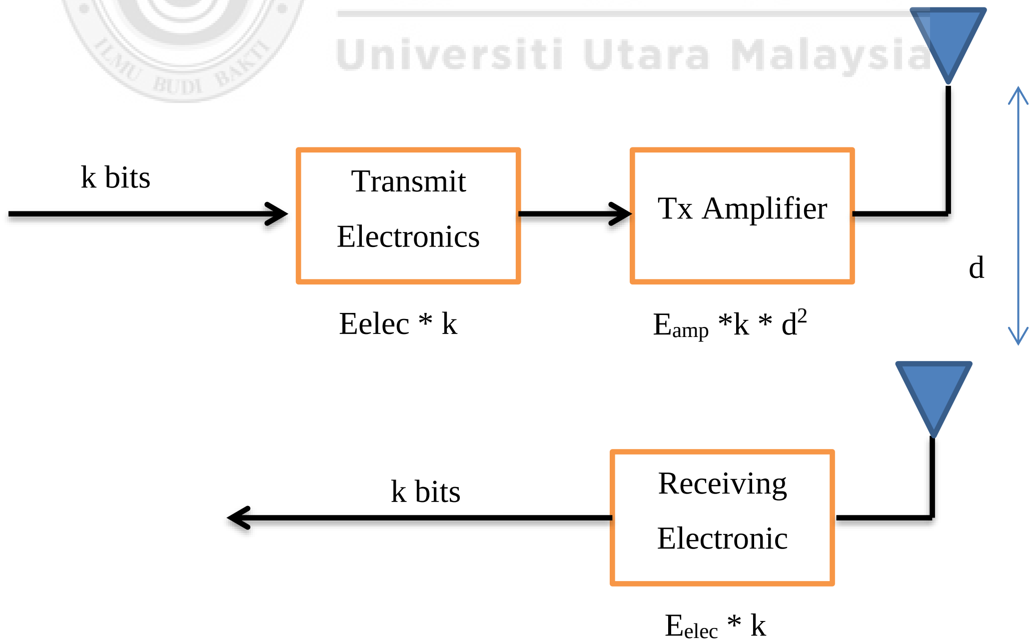


Figure 3.9. First Order Radio Model

This research makes the same assumptions as in [10], [27], i.e., the radio channel in the network is symmetric, which means that the energy required to transmit a packet from A node to B node is the same energy required to send the same packet from B node to A node.

3.5.5 Verification and Validations

Verification is to determine that the mechanisms are transformed from one form to another form correctly with sufficient accuracy [111]. In this research verification step is pursued by transforming the flowchart or pseudo code to execute program in computer for all three mechanisms (BCM for chain construction, CHS for chain head selection and NHC for next hop). This means that all mechanisms should be transformed to C++ code since ns-3 [112] simulator running with C++ programing language. These mechanisms should be coded and verified without any bugs or errors (correctly) [113]. Eclipse C/C++ Developing Tools (CDT) is used for the verification purpose because it has advanced function for C++ developers including debugger, parser, launcher and makefile generator. Finally, at the end of this step all mechanisms should be coded into C++ language that will be free from errors, bugs, sematic and syntax errors [114].

Validation is defined as "substantiation that is a computerized model within its domain of applicability possesses a satisfactory range of accuracy" [115]. Validation is performed to make sure that all mechanisms meet their intended requirements in terms of methods and results obtained. This research validates the three proposed mechanisms in existing chain based protocol to ensure that these mechanisms can work correctly and meet the expected result according to execution behavior for each of them in simulation environment by comparing with other valid models (mechanisms). Furthermore, the conceptual model validity determines: first, the assumptions underlying the conceptual model are correct; and second, the model represents the problem entity and the model's structure, logic, and mathematical and causal relationships are 'reasonable' for the intended purpose of the model [116].

Since the syntax and semantic errors are impossible to detect in text editor (that is used in ns-3), Eclipse IDE C/C++ Mars version provides powerful environment used as compiler, debugger and language editor. After ns-3 is integrated with Eclipse, the C++ compiler and debugger are used to complete the task within the Eclipse environment. The Linux command line is used to run the programming script as the ns-3 developers recommend it.

Furthermore, validation for BCM, CHS and NHC mechanisms are divided into two parts. First is to confirm that the mechanisms' equation is programmed accurate as required. Second is to insert the whole mechanism inside benchmark protocol (PEGASIS) in WSN environment and investigate if they can give some results. For BCM, equations are implemented in MATLAB and ns-3 and then some number of columns is put if it gives the same result exactly. It means that the BCM equation meets its requirement and is implemented correctly in ns-3. Finally, the whole BCM is implemented inside PEGASIS to ensure that BCM can work correctly and it gives some results based on one performance metric. The CHS and NHC mechanisms' equations are validated (by taking random round) and calculated the CHS_{factor} and NHC_{factor} mathematically to find out which nodes are nominated to be CHs and NHC. Next, the results are compared with decisions from ns-3. The whole CHS and NHC mechanisms are inserted inside PEGASIS whether it gives some results, which means that each mechanism is successfully implemented in WSN environment.

3.6 Descriptive Study (DS-II)

The DS-II is the last step within the DRM research methodology procedures. In this stage, the DCBRP routing protocol's results are presented that offers comprehension. Furthermore, the data collection, analysis, descriptions, figures or graphs are intended to evaluate the DCBRP routing protocol's with other existing protocols. This is considered very important to study and understand the effectiveness of previous stages of this research. Scenario iteration running is required to make sure that the simulation is working in a steady-state situation. Moreover, this study observes contributions achieved by the proposed protocol to measure the potential in the chain-based routing concept with specific performance metrics.

3.6.1 Performance Evaluation

Evaluation is the main part of DS-II for DRM methodology. Therefore, choosing the evaluation method is a very important step in this stage for any research or project [117], especially when comparison is needed between several protocols to present which protocol outperforms others [118]. In general, there are three methods to evaluate the network performance [119], [120]. These include the simulation, analytical modeling and measurement. In research and development of networking area, the analytical modeling and measurement are important during the conceptual phase, but this is typically infeasible due to financial and technical constraints.

Simulation method is used in this research to evaluate protocols. Choosing the realistic simulation tools is very essential to develop meaningful experiments and carry out the real behaviors for proposed protocol in deferent phases [121].

There are many network simulators that can be used for WSN such as OMNET++ [122], [123], ns-2 [124], OPNET [125] and PROWLER [126]. ns-2 is well-known open source object oriented event based network simulator, that is widely used in the network research [127]. ns-2 performs simulations of routing protocols in the scenario of wireless or wired communication networks. There are various advantages which make it a beneficial simulation tool, like providing support to perform simulation on the various protocols and the ability to visualize detailed network traffic. However, ns-3 [112] is the new major version of ns-2 with clear documentation and supporting by academic networks community in terms of protocols implementation and errors debugging as well as it is fully compatible with C++ Eclipse platform. Further details about various simulators can be found in [128]–[130].

3.6.2 Network Simulator 3 (ns-3)

ns-3 [112] is a discrete-event network simulation and it is powerful network simulation tool for protocol interaction, protocol design and large-scale performance issues for educational used. The ns-3 is considered as a new major version of ns-2. ns-3 is developed in C++ wrapped by Python, as it is clear in ns-3 documentation [131]. In last few years, a lot of educational researchers work in ns-3 due to its specification submitted in [132]–[142] with different areas in the networks.

3.6.3 The WSN in ns-3

The wireless sensor network application conducted one of the IEEE standard 802.11 (*WiFi*) or 802.15.4 (*lr-wpan* 2006) for MAC layer implementation. The current ns-3 works very well with full functionality within WiFi and it is compatible with other important classes such as *Energy* model, *Battery* model and *Netanim* model. However, *Lr-WPAN* class has some limitations with these models. In the routing protocol layer, there is no difference what are used when the *First Order Radio Model* is utilized for energy consumption calculations. Following are some important ns-3 classes which are used in this research:

- *Gnuplot*: it is used to generate ready plotting file within commands from a set of datasets which are collected during simulation time. It uses a kind of file generation that helps to save some of important statistical information related with results.

- *NodeContainer:* Typically, ns-3 helpers can work with more than one node at a same time. *NodeContainer* can hold multiple Ptr <Node> which are used since *NodeContainer* can define more than one node pointer and work with them by *NodeContainer* object name.

- *InternetStackHelper:* This helper enables *pcap* class and *ascii* class tracing of events in the Internet stack associated with a node.

- *MobilityHelper:* this helper is used to assign the mobility or the position to the nodes. According to the scenario in this research *MobilityHelper* was used to set the coordinators (x,y) for each node in deterministic method. Furthermore, the distance between the nodes can be calculated by this class immediately for more necessary computations.

- *YansWifiChannelHelper:* it works together with *YansWifiPhyHelper* for assigning channels and physical layer for nodes.

- *WifiHelper:* this class helps to create a large set of *WifiNetDevice* objects and to configure their attributes during creation.

- *NqosWifiMacHelper:* this class helps to create non QoS enabled in MAC layer for *ns3::WifiNetDevice.*

- *NetDeviceContainer:* this class helps to install MAC address and a queue in all nodes in the same time by using *netdevice* helper.

- *UdpServerHelper, ApplicationContainerfor* the server*, UdpClientHelper,* and the important part *ApplicationContainer* for clients: these classes and helpers are necessary for installing the application, whether it is UDP of TCP application. All requirements setting, used in this research, such as packets size, start sending, end sending, and number of packets are such that one packet from each node in each round is sent rather than depending on simulation time.

- *AnimationInterface:* this important class is used for visualizing the network after running. Furthermore, it is used for adding descriptions and colours for the nodes.

- *FlowMonitorHelper:* this helper is used to enable IP flow monitoring for a set of nodes and provides very useful statistical information about the network behaviours such as txPacketsum, rxPacketsum, DropPacketsum, LostPacketsum, Delaysum, txBytessum, and rxBytessum. Therefore, many information can be obtained through this class.

- *LrWpanHelper*: this is a class for managing and creating IEEE 802.15.4 (Lr-WPAN 2006) standard *netdevice* object and configuring their attributes.

3.6.4 Simulation Setup

This research uses the deterministic sensor nodes deployment in sensing network area. Therefore, the following parameters and settings in Table 3.1 are required to evaluate the DCBRP routing protocol including its three proposed mechanisms, which are BCM, CHS, and NHC mechanisms.

Moreover, data fusion will reduce number of packets send from the network to the BS, where each node fuses neighbor's data with its data and the output will be one packet with same size. While in the non-data fusion scenario, number of packets will be the same number of live nodes in the network to study the protocols behavior in heavy load. Therefore, for comprehensive performance evaluation, both approaches (data fusion and non-data fusion) are applied with same energy required for each bit as in [18], [27], which is 5 nJ/bit for each packet.

In addition, the sensing area will be 100 X 100 m with 90 nodes, deterministic deployment with 10m between nodes, which is used by many researchers in WSN [18], [28], [100], [142] . While the base station is located in (50,120) (which is out of the sensing area) to investigate the CH performance and this is in the same direction with all previous protocols discussed in Chapter two. Initial energy for all nodes is 0.5, 2 joules in scenario 1, 2 respectively to study the DCBRP protocol behaviors in different settings, as used in [99], [144]. The UDP traffic is used with packet size 2000 bits which is popular and used by various WSN researchers [18], [28], [100], [145]. Furthermore, queue size is set as 50 packets and this helps the CHs to deliver all the network data to BS. This is the same setting used by transport layer researchers such as [114]. Moreover, First Order Radio model is used as energy consumption for data transmission E_{TX}, E_{RX} and E_{amp} which is utilized by all protocols in the literature. Finally, the 802.11 standard version is used in MAC layer, which is used in [26].

Moreover, the DCBRP routing protocol is compared with the closest routing protocols in the same deterministic node deployment which are CCM and TSCP. CCM routing protocol has significant contribution in terms delay because of the clustering approach in intra connections between CHs, while TSCP gives advantage for energy consumption by applied the chain approach in inter and intra connection, therefore they are suitable to measure the ability of DCBRP routing protocol.

Table 3.1

Simulator Parameters

Parameters	**Value in scenario 1**	**Value in scenario 2**
Energy for data fusion	5 nJ/bit/packet	-
Fusion strategy	Data fusion	Without data fusion
Sensing Area	100 *100 m	100 *100 m
Number of nodes	90	90
BS Location	(50,120)	(50,120)
Initial nodes Energy	0.5 J	2.0 J
Packet length	2000 bit	2000 bit

Network traffic	UDP	UDP
Queue Size	50 Packets	50 Packets
Nodes deployment	Deterministic	Deterministic
Distance between nodes	10 meters	10 meters
Energy consumption model	First Order Radio Model	First Order Radio Model
Energy Amplifier	100 pJ/bit/m^2	100 pJ/bit/m^2
Energy for Send/Receive (open circuit)	50 nJ/bit	50 nJ/bit
Routing Protocol	DCBRP, TSCP, CCM	DCBRP, TSCP, CCM

3.6.5 Evaluation Metrics

The key step in all performance evaluation parts are the performance metrics selection [146] because they measure the DCBRP routing protocol performance in comparison with others. Therefore, selecting the proper performance metrics is very important to investigate the behaviors of the protocol from different perspectives. Different metrics give us the complete view on the performance of the proposed mechanism and the way it is compared with others.

For this research, the performance of the proposed protocol are compared with two deterministic chain-based routing protocols, named CCM and TSCP (these protocols were discussed in details in Chapter two). CCM and TSCP have the same intra connection and some difference in inter connection with slight variation of chain head and main head selection. The performance evaluation based on the objectives of this research is done to make sure that the proposed protocol outperforms other protocols. This performance evaluation is based on the context of end-to-end delay, network lifetime, energy consumption and delay*energy metrics. The detail of these metrics is presented in the next sections.

3.6.5.1 End-to-End Delay

Delay is considered as the main drawback point in the chain-based routing protocols therefore, it is important to enhance the delay criteria in any designing. The primary temporal evaluation metric in the literature can be divided into two sub metrics.

A. Average delay every 100 rounds: this can be calculated by dividing the summation of end-to-end delay for all packets by the total number of packets in this round:

$$AveDelay = \sum_{P=0}^{Last\ p} Trx - Ttx \Big/ NumberOfPackets \tag{3.3}$$

A. Average End-to-End delay for all network lifetime: this metric can measure the overall delay during the difference between the protocols lifetime, which is represented by:

$$OverAllDelay = \sum_{round=1}^{last\ round} AvergDelay \Big/ LastNodeDieRound \tag{3.4}$$

3.6.5.2 Network Lifetime

The main performance metric in WSN is the network lifetime due to the limitation of power resources in all nodes (all nodes depend on battery as power supplier) [14]. Therefore, network lifetime is considered as critical issue for researchers when designing routing protocol for WSN. In this research, it is important to measure the following criteria that are related to network lifetime metrics:

a- Round for the first node die (FND): this refers to that round when first node dissipates all its energy [147]–[149].

b- Round to 50% of the node die: this refers to the round when half number of nodes dies [150], [151].

c- Round for all nodes die (LND): this refers to the round when all nodes dissipate all their energy.

3.6.5.3 Energy Consumption

Almost all evaluation strategies in wireless sensor networks include some form of energy metrics [14]. There are three energy metrics that are commonly used by the routing protocol researchers to investigate the energy efficiency of the DCBRP routing protocol and to compare it with other existing protocols:

a- All sensor nodes energy consumption per round by energy consumption in every round: it is considered as important metric in calculating the overall energy dissipated for all sensor nodes per round during the network lifetime, as in Equation 3.5.

$$E_{consu.in\ round\ r} = \sum_{i=1}^{number\ of\ nodes} E_{consu.in\ node\ i} \tag{3.5}$$

b- Average energy consumption by the nodes in rounds: this is to study how the reducing energy consumption can prolong the network lifetime.

$$E_{Av,Ene.consu} = \sum_{firstround}^{lastround} E_{cons.allnodes} \Big/ N_{totalno.round} \tag{3.6}$$

c- Average energy consumption by CHs in the network: Average energy consumption by the CHs in rounds

$$E_{Ave\ E\ consu\ by\ CH} = \sum_{firstround}^{lastround} E_{ene.cons.byCH} \Big/ N_{totalNo.round} \tag{3.7}$$

3.6.5.4 Energy*Delay

This metric was suggested by Lindsey in [143] and was used by chain-based routing researchers in WSN to combine the importance of energy consumption with delay that comes from chain-based concept. This interesting metric can be calculated using Equation 3.8.

$$Energy * delay = E_{total\ Econs.in\ round\ r} * D_{delay\ to\ dilever\ all\ data} \tag{3.8}$$

3.7 Summary

This chapter illustrated the methodology used in this research. Design Research Methodology (DRM) is used to achieve all the research steps started from area of understanding to literature review, then problem identification and after that the design of protocol mechanisms, which are BCM, CHS and NHC. These mechanisms build the DCBRP routing protocol in three phases. The Chapter also presents the validation and verification methods for complete DCBRP design. ns-3 network simulator is selected for evaluation step with other existing routing protocols in WSN with the context of some famous performance metrics. The next chapters will give more details about BCM, CHS and NHC mechanisms with the performance evaluation of DCBRP routing protocol.

CHAPTER FOUR
DCBRP ROUTING PROTOCOL FOR WSN

4.1 Introduction

The main goal of this thesis is to propose deterministic chain based routing protocol for wireless sensor networks. DCBRP considers energy efficient routing protocol which aims to prolong the lifetime of network nodes, reduce the power consumption and delay when all nodes deliver their data to the BS. DCBRP routing protocol consists of three mechanisms, Backbone Construction Mechanism (CHS), Chain Heads Selection mechanism (CHS), and Next Hop Connection mechanism (NHC). This chapter presents these mechanisms in detail starting from Section 4.2 which is related to the BCM then its design in Section 4.2.1, while the BCM implementation, verification, and validation are presented in Sections 4.2.2 and 4.2.3, respectively.

Section 4.3 discusses the CHS mechanism with detail explanation of its design in Section 4.3.1, whereas the implementation is presented in Section 4.3.2. Next, the verification and validation are elaborated in Section 4.3.3. In addition, NHC mechanism is discussed in Section 4.4 and the design of NHC mechanism is illustrated in Section 4.4.1. Furthermore, Section 4.4.2 shows the implementation of NHC and Section 4.4.3 presents the verification and validation of NHC mechanism in detail. Finally, Section 4.5 provides the summery of the chapter.

4.2 Backbone Construction Mechanism (BCM)

Chain construction phase has the highest impact on the performance of the routing protocols' behavior especially in the chain-based routing protocols. According to literature, as explained in Chapter Two, every protocol has different ways to construct the chain of nodes connection (main chain construction). Some of the protocols depend on intelligent algorithms to build the main chain. For example, PEGASIS constructs its chain based on Greedy algorithm, while other protocols use ACO, Genetic, or Simulate annealing to route the packets from source to destination (base station). In addition, the deterministic node deployment with grid topology routing protocols like CCM and TSCP consider the sequence approach to change the role of the nodes from normal node to CHs chain and so on.

Within the DCBRP routing protocol, BCM mechanism is responsible for constructing the main chains (i.e., it constructs the vertical and horizontal chains) by dividing the sensing nodes into specific number of clusters. Every cluster has three or two columns (depending on the network size) to reduce the negative affect of the single and long chain. Moreover, in order to produce the importance balancing between the numbers of hops count for all packets trip and the end-to-end delay.

4.2.1 The Design of BCM Mechanism

In this section, the backbone chains will be calculated by the BS depending on the number of node's columns in the sensing network to formulate the number of clusters and columns for each cluster. The BS can compute the main chain and broadcast it to all the network nodes by achieving the following three steps:

Firstly, the BS will calculate the number of clusters in the network to divide the network into specific number of clusters. Each cluster has a maximum of three and minimum of two columns. This is to ensure that every node has more than one option to select the next hop connection to apply energy balancing in the nodes' chain and to avoid data loss for single and long chain. Moreover,

- Intermediate node dying in single chain will cause data lost for all previous nodes.
- Choosing four columns in the cluster will make heavy data transfer in the next hop node and it will deplete its energy very quickly comparing with other and so on with more than four.

Therefore, BCM makes three columns in each cluster and two in the last cluster. If the remaining two clusters (the last and before last) have two columns then the remaining are four columns after dividing the number of columns by 3. In addition to calculate how many clusters in the specific network exist, the BS needs to know the number of columns in this network as global knowledge (as assumed in Chapter Three).

From the above requirements for BCM mechanism design and global knowledge assumptions, Table 4.1 is constructed which offers some of network topologies scenario probabilities to generate the mathematical formulas:

Table 4.1

BCM Mechanism Requirements Depends on no. of Columns

Number Of columns	Cluster1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
3	**3 columns**	/	/	/	/	/
4	**2 columns**	**2 columns**	/	/	/	/
5	**3 columns**	**2 columns**	/	/	/	/
6	**3 columns**	**3 columns**	/	/	/	/
7	3 columns	**2 columns**	**2 columns**	/	/	/
8	3 columns	**3 columns**	**2 columns**	/	/	/
9	3 columns	**3 columns**	**3 columns**	/	/	/
10	3 columns	3 columns	**2 columns**	**2 columns**	/	/
11	3 columns	3 columns	**3 columns**	**2 columns**	/	/
12	3 columns	3 columns	**3 columns**	**3 columns**	/	/
13	3 columns	3 columns	3 columns	**2 columns**	**2 columns**	/
14	3 columns	3 columns	3 columns	**3 columns**	**2 columns**	/
15	3 columns	3 columns	3 columns	**3 columns**	**3 columns**	/
16	3 columns	3 columns	3 columns	3 columns	**2 columns**	**2 columns**
17	3 columns	3 columns	3 columns	3 columns	**3 columns**	**2 columns**
18	3 columns	3 columns	3 columns	3 columns	**3 columns**	**3 columns**

The equation is derived from the assumption that it is one of the strongest strategies to validate the correct method for proving an equation [152]. In this research, the proposed strategy is motivated by the mathematical induction to prove BCM mechanism equations. Moreover, as Daniel mentioned in his mathematical book in [152] that the theorem can be obtained as follows:

Conjecture + Proof =Theorem

Therefore, the BCM mechanism Conjecture can obtain its theorem from Table 4.1 as follows:

Theorem 1: The number of clusters in BCM mechanism is $\left\lceil \frac{N_{\text{columns}}}{3} \right\rceil$, where $\lceil \ \rceil$ refers to the biggest nearest integer number and $N \geq 3$.

Proof*:*

This Theorem will be proved by mathematical induction:

Let N equals the number of columns,

Let $N = 3$ then

The number of cluster = $\left\lceil \frac{N_{columns}}{3} \right\rceil = \left\lceil \frac{3}{3} \right\rceil = 1$ cluster

Hence, this is true that there is 1 cluster if n = 3, where every three columns in BCM mechanism have one cluster.

Assume that the formula is true for n= k for $k \geq 3$,

then the number of clusters = $\left\lceil \frac{k}{3} \right\rceil = d$.

Note that BCM mechanism is based on 3, and

Needs to prove at n = k +3 for $k \geq 3$, so

The number of clusters = $\left\lceil \frac{k+3}{3} \right\rceil = \left\lceil \frac{k}{3} \right\rceil + \left\lceil \frac{3}{3} \right\rceil = d + 1$

Hence, this is true that for k + 3 columns there is d+ 1 clusters, as BCM required every three columns in one cluster, and when the n increases by three, the d is increased by one.

From the above theorem, the number of clusters in any network can be calculated by the following equation:

$$N_{cluster} = \left\lceil \frac{N_{columns}}{3} \right\rceil \quad (4.1)$$

Finally, to prove that this Equation works properly, it can be tested with any number of columns. For example, number of columns = 17, 18, and 19:

$$N_{cluster} = \left\lceil \frac{N_{columns}}{3} \right\rceil = \left\lceil \frac{17}{3} \right\rceil = \lceil 5.666 \rceil = 6 \ Clusters$$

$$N_{cluster} = \left\lceil \frac{N_{columns}}{3} \right\rceil = \left\lceil \frac{18}{3} \right\rceil = \lceil 6 \rceil = 6 \ Clusters$$

$$N_{cluster} = \left\lceil \frac{N_{columns}}{3} \right\rceil = \left\lceil \frac{19}{3} \right\rceil = \lceil 6.33333 \rceil = 7 \ Clusters$$

Conclusion: The BS uses Equation 4.1 to obtain the number of clusters in any network, where, $N_{cluster}$ represents the number of clusters in this network, ⌈ ⌉ is mathematic sample that returns the nearest biggest integer number for any fraction number, while, $N_{columns}$ refers to the number of columns in this network.

The BS then needs to calculate the number of columns in each cluster in order to construct all the network chains, as shown in Figure 4.1. Equation 4.2 achieved this task by using the number of columns. It will provide exactly the number of columns in the last two clusters (which are three or two in each cluster), and the rest have three columns by default in all networks, as can be seen in Table 4.1.

Theorem 2: The number of columns in last and before last clusters is

$N_{columns} \bmod 3 = \begin{cases} 1, then\ c_{n-1}, c_n = 2, 2 \\ 2, then\ c_{n-1}, c_n = 3, 2 \\ 0, then\ c_{n-1}, c_n = 3, 3 \end{cases}$ for $N \geq 3$ in the BCM mechanism.

Proof:

This Theorem will be proven by mathematical induction:

Let N equals the number of columns, c_{n-1}, c_n refer to the number of columns in the last and before last clusters.

There are three cases in this prove:

Case 1: $N_{columns}$ mod 3 = 1

Let N = 4 (first number), so 4 mod 3 = 1 then c_{n-1}, c_n = 2, 2. Since it cannot have single column in cluster, therefore, one column is brought from the C_{n-1} to become 2, 2.

Hence, this is true that c_{n-1}, c_n = 2, 2 if the number of columns is 4 based on BCM specifications.

Assume that the formula is true for N = k; k $\geq$ 4, the k mod 3 = 1 then c_{n-1}, c_n = 2, 2

Needs to prove at N = k +3 for k $\geq$ 4, so

k +3 mod 3 = 1, then c_{n-1}, c_n = 2, 2 because a single column cannot be put in the cluster, so one column will be brought from the C_{n-1} to become, 2, 2.

Hence, this is true that c_{n-1}, c_n = 2, 2 if all clusters have three columns and last four columns will be divided for two clusters.

Case 2: $N_{columns}$ mod 3 = 2

Let N = 5 (first number) then 5 mod 3 = 0 then c_{n-1}, c_n = 3, 2

Hence, this is true that c_{n-1}, c_n = 3, 2 if the number of columns is 5 based on BCM specifications.

Assume that the formula is true for N = k; k $\geq$ 4, the k mod 3 = 2

Needs to prove at N = k +3 for k $\geq$ 4, so

k mod 3 = 2 then k +3 mod 3 = 2

So, c_{n-1}, c_n = 3, 2 for any number of k or k+3 because BCM allows two columns to create last cluster.

Hence, this is true that c_{n-1}, c_n = 3, 2 if the remaining 2 columns from the mod functions and BCM accept 2 columns in the last cluster.

Case 3: $N_{columns}$ mod 3 = 0

Let N = 6 (first number) then 6 mod 3 = 0 then c_{n-1}, c_n = 3, 3

Hence, this is true that c_{n-1}, c_n = 3, 3 if the number of columns is 6 based on BCM specifications.

Assume that the formula is true for N = k; k $\geq$ 4, the k mod 3 = 0

Needs to prove at N = k +3 for k $\geq$ 4, so

k mod 3 = 0 then k +3 mod 3 = d, So, c_{n-1}, c_n = 3, 3 for any number of k.

Hence, this is true that c_{n-1}, c_n = 3, 3 if N is divisible by 3, for any number N based on the BCM mechanism concept.

BCM mechanism needs to calculate only the last cluster's columns C_n and before last C_{n-1}, and from Table 4.1C_n and C_{n-1} have three probabilities only. Therefore, **mod** function will be used to obtain its value from the following formula:

$$\boldsymbol{N_{columns}} \textbf{ mod 3} = \begin{cases} \boldsymbol{1, then\ c_{n-1}, c_n = 2, 2} \\ \boldsymbol{2, then\ c_{n-1}, c_n = 3, 2} \\ \boldsymbol{0, then\ c_{n-1}, c_n = 3, 3} \end{cases} \quad (4.2)$$

where, $N_{columns}$ refers to the number of columns in the network, while C_{n-1}, C_n represents how many columns in the last and before last clusters in the network, respectively.

Furthermore, for more explanation, Equation 4.2 takes any number of columns, for example 17, 18, 19, and calculates the number of columns in the last and before last clusters:

$N_{columns}$ mod 3 = 17 mod 3 = 2 So, the C_{n-1}, C_n= 3, 2

$N_{columns}$ mod 3 = 18 mod 3 = 0 So, the C_{n-1}, C_n= 3, 3

$N_{columns}$ mod 3 = 19 mod 3 = 1 So, the C_{n-1}, C_n= 2, 2

and this comes exactly with BCM conjecture which can be applied for any number of columns.

By applying both Equations 4.1 and 4.2, the BS can calculate the number of clusters in this network and the number of columns in each cluster. Moreover, it is ready for constructing the vertical and horizontal chains. Finally, the horizontal nodes in each cluster are connected as a chin form for every row. This small chain has two or three nodes only. Then, the intermediate nodes for every cluster, which has three columns, will construct vertical main chain in this cluster while choosing right or left nodes to construct the vertical chain for the cluster, which has two columns, in a random way. Therefore, the result from BCM will be one of these Figures in 4.1a, 4.1b or 4.1c depending on the number of column and above Equations.

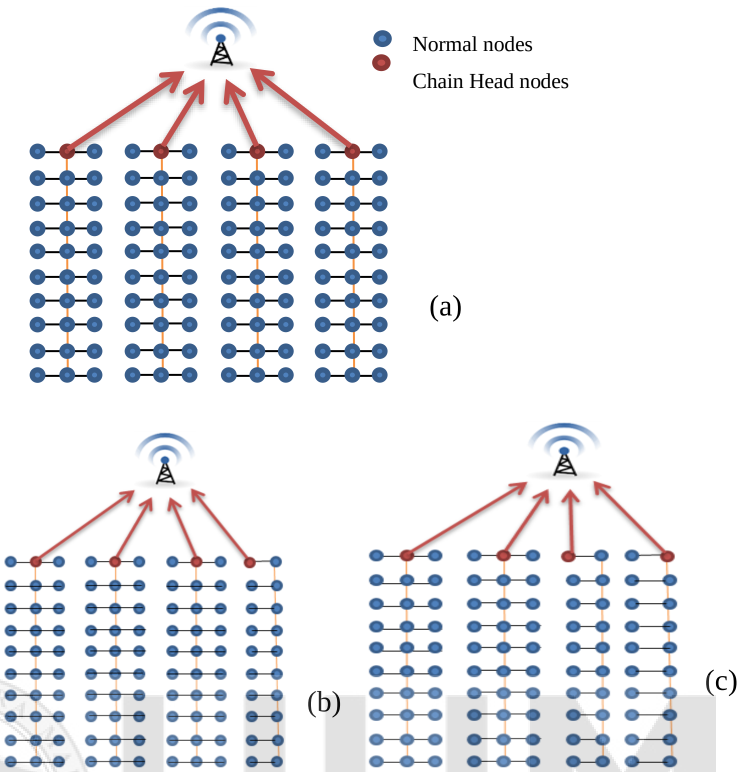


Figure 4.1. Chains Constructed by BCM in DCBRP Protocol

In addition, BCM increases the robustness of the network by avoiding single and long chains, produces more than one option for packets routing, avoids route failure as long as possible and reduces the number of chains. Therefore, for these reasons BCM choses the number 3 as base of its work because if 2 is chosen then the number of chains will increase, so the power consumption of nodes will also increase. Moreover, if 4 is chosen then load on the main chain nodes will be double which may cause early dying of the node and shorten the network lifetime.

4.2.2 The Implementation of BCM Mechanism

BCM considers the first mechanism in DCBRP protocol working to build the backbone chain in the network. During BCM mechanism, the BS needs to compute the two important parameters depending on the number of columns in the network (this is already given to BS by assumptions). First, it is the number of clusters in the network and second, it is the number of columns in each cluster. In addition, the rest of DCBRP protocol will depend on the result of BCM mechanism to take the necessary action, which starts from main chain construction and ends with data aggregation. For this reason, BCM is considered a very important unit in DCBRP protocol. This research needs to be implemented in a way that the research meets the expectations to ensure that BCM meets the protocol designer requirements.

Figure 4.2 shows the pseudo code of first part of BCM to compute the number of clusters in the network and calculate that how many columns exist in each cluster.

```
Procedure 1: NumberOfClusters

  Receive NumberOfColumns
        NumberOfClusters ← ceil ( NumberOfColumns / 3.0 )
 return (NumberOfClusters)
End Procedure1

Procedure2: NumberOfColnmnInEachCluster

  Receive NumberOfColumns , NumberOfClusters
        Integer TMP
        Integer Cluster [NumberOfClusters - 1]
                TMP ← NumberOfColumns % 3
Check TMP
        if    TMP equal to 0    then
                {Cluster[NumberOfClusters - 2] ← 3;
                 Cluster[NumberOfClusters - 1] ← 3;
                }
   else if TMP equal to 1    then
{Cluster[NumberOfClusters - 2] ← 2;
                Cluster[NumberOfClusters - 1]  ← 2;
                }
        else
                {Cluster[NumberOfClusters - 2]  ← 3;
                Cluster[NumberOfClusters - 1]  ← 2;
               }
 for i=0 to NumberOfClusters-3   do
        Cluster[i]=3
        End-for
 return Cluster
End Procedure2
```

Figure 4.2. Pseudo-code for First Part of BCM

During *NumberOfClusters* procedure, the number of columns received in step one are used to be divided by 3, and the result will process the ceil function which make the fraction number equal to nearest up real number to meet the BCM requirement (Equation 4.1). Then the procedure will return the number of clusters in this network and BCM will be ready now to start the second mechanism.

The second procedure (*NumberOfColnmnInEachCluster)* in step one received the number of columns and the number of clusters in this network. The TMP variable is calculated by using mod function or reminder operation between the number of columns and number 3. After that, the procedure in the next step will examine the TMP variable to provide the right number of columns to the initial and last clusters as well as assigning number 3 to all the remaining clusters, as mentioned in Equation 4.2. Finally, the procedure returned to *Cluster* array which has all the information about the number of columns in each cluster.

BCM mechanism now has all parameters to start the vertical and horizontal connection among sensor nodes in each cluster. Figure 4.3 illustrates the pseudo code of connection part of the BCM in multi hop method.

Procedure 3: *HorizontalAndVerticalConnection*

```
For i=0 to  (NumberOfClusters – 1) do
    For j=0 to  (NumberOfRows – 1) do
        connect Node[j], Node[j+1], Node[j+2]
        connect Node[j+1] , Node[j+3]
    End-for
End-for
End Procedure 3
```

Figure 4.3. Pseudo-code of Horizontal and Vertical Connection Procedure in BCM

During *HorizontalAndVerticalConnection* procedure, all sensor nodes are connected to each other based on the functionality of BCM mechanism. Horizontal connection is presented in the first step of the procedure number 3 and the vertical connection in the next step.

4.2.3 The Verification and Validation of BCM Mechanism

Verification is important step to ensure that BCM mechanism is transferring correctly from conceptual model to computer or simulation language. As mentioned in Chapter Three, verification is required to validate that pseudo code for BCM has successfully programmed in the simulation environment and implemented with free of bugs and error.

The validation needs to be performed to ensure that BCM mechanism reach its requirements. In other words, BCM mechanism is applicable in chain-based routing protocols and meets the first phase specifications, as mentioned in Chapter Three. The validation level of BCM mechanism will focus on testing the relationship between the number of columns with the final form of the chain in the network.

Therefore, to reach the overall acceptable validation of BCM mechanism, it needs to pass two parts of validation. The first one is the mathematical model of BCM by implementing both BCM Equations in MATLAB and ns-3, and the second part is the simulation model validation.

4.2.3.1 Validation of Mathematical Model of BCM

The main purpose of the BCM mechanism is to build the backbone chains of DCBRP protocol, as shows in Figure 4.1a, b or c by using mathematical Equations 4.1 and 4.2, respectively. Furthermore, BCM mechanism is designed to reduce the delay caused by the single long chain through dividing the network nodes into specific number of clusters.

Therefore, the validation of BCM will depend on the dynamic technique that is commonly used in model verification and validation [153].The result obtained from ns-3 simulator needs to be compared with the result from analytical tools in different number of conditions. Therefore, Table 4.2 presents both results which are obtained from ns-3 simulator and MATLAB software as analytical and mathematical tool. It is obvious that the results are exactly the same for both tools. It is to make sure that whatever tools are used to program the equations, results must be of the same values.

Table 4.2

Validation Result from ns-3 Simulator and MALAB Tools

No	Number of columns	Number of rows	Equation 1 (number of clusters)	Equation 2 (no. of columns in last , before last cluster)	Results from ns-3	Results from MATLAB
1	3	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{1,(3)}	{1,(3)}
2	4	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{2,(2,2)}	{2,(2,2)}
3	5	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{2,(3,2)}	{2,(3,2)}
4	6	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{2,(3,3)}	{2,(3,3)}
5	7	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{3,(2,2)}	{3,(2,2)}
6	8	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{3,(3,2)}	{3,(3,2)}
7	9	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{3,(3,3)}	{3,(3,3)}
8	10	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{4,(2,2)}	{4,(2,2)}
9	11	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{4,(3,2)}	{4,(3,2)}
10	12	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{4,(3,3)}	{4,(3,3)}
11	13	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{5,(2,2)}	{5,(2,2)}
12	14	10 rows	$\left\lceil \frac{N_{columns}}{3} \right\rceil$	$N_{columns}\ \boldsymbol{mod}\ (3)$	{5,(3,2)}	{5,(3,2)}

4.2.3.2 Validation of BCM in PEGASIS Protocol

Power Efficient Gathering in Sensor Information Systems (PEGASIS) [27] is widely used in wireless sensor networks, therefore, it will use to determine whether the simulation model of BCM output behavior has attained the requirements of its design. This is suitable for BCM mechanism because it depends on distance to construct its chain, therefore, the comparison is done to ensure that the BCM mechanism works properly in WSN environment and provides acceptable results. The delay metric is used to make this comparison between the standard PEGASIS and the PEGASIS with BCM mechanism. BCM will divide the network into clusters to reduce the delay caused by single/long chain. Table 4.3 presents the percentage of enhancement of delay for PEGASIS-BCM and the delay obtained from standard PEGASIS. It shows the ability of BCM mechanism to reduce the delay in data fusion scenario and without data fusion scenario and it works properly in PEGASIS protocol.

Table 4.3

Validation of BCM inside PEGASIS Protocol

Based on standard PEGASIS	Average delay with data fusion scenario	Average delay without data fusion scenario
Enhancement of PEGASIS-BCM	61.64%	69%

Furthermore, the number of chain and number of hops directly affect delay; in PEGASIS, one chain was built for all network nodes, thus all packets will suffer from the multi hop during traveling from source to the BS. While in PEGASIS-BCM, the network is divided into three clusters (all simulation settings as mentioned in Chapter Three) and multi chain in row that will help packets to reach the BS in less number of hops comparing with standard PEGASIS. The CH position is important factor for delay and therefore PEGASIS selects CH randomly in the network. The average delay obtained from 10 simulation rounds for different places of the CH. Moreover, this comparison shows that BCM mechanism is valid in PEGASIS protocol and it has positive effect on this protocol.

4.3 Chain Head Selection Mechanism (CHS)

Chain head selection has higher priority phase in the most routing protocols in WSN, especially in chain-based approach, where all protocols presented in Chapter Two have this mechanism in some way. Normal sensor nodes sense data and transmit their data to the nearest node in the same chain, hence will spend little energy for this task until one of them become the chain head or the main head in the network. At this moment, the chain head is responsible to transfer all the chain (or network) data to the BS. Therefore, it will spend a lot of energy to ensure that all data transfer is successful.

Furthermore, the way of selecting the proper node to be the chain head is important to prolong the network lifetime and keep all sensor nodes in connection. Moreover, the number of chain heads can directly affect the performance of protocols by dividing the responsibility of data delivering to the BS and dividing the required energy on the number of chain heads [1], [24], [25]. It is not only used for energy consumption purpose but also for reducing the delay caused by single gateway for networks.

According to the discussion in Chapter Two on how to select the chain heads in the chain-based routing protocols, there are many ways to assign this role to the correct node. Such methods are: PEGASIS protocol is used randomly to select the chain head to make sure the first node that dies is in the random position in the sensing area and rotate selection for same node after *i* round for *N* number of nodes by applying Equation 4.3.

$$CH = i \bmod N \tag{4.3}$$

where, *i* is the number of rounds and *N* is the number of nodes in the network.

While, CCM and TSCP use sequence way for chain head selection (remaining energy for nodes) and remaining energy for selecting the main head (connect with the BS) with ignoring the node position according to BS, as in Equation 4.4.

$$S_{factor} = E_{remaining} \tag{4.4}$$

Where, $E_{remaining}$ refers to the remaining energy in the sensing node, while S_{factor} is the selection factor for choosing the main head. As mentioned earlier, there are many shortcomings of this approach, which have been discussed in Chapter Two.

The most appropriate chain head selection can be found with other routing protocols because they are depended on the residual energy and the distance with the BS such as [96], [98]. However, these do not consider the ability of nodes for data delivering to BS. From these points, CHS mechanism considers proactive selection to ensure the relevance of the residual energy and it is the nodes' ability for data delivery (node ability refer to how much energy is consumed if this node is selected as CH).

4.3.1 The Design of CHS Mechanism

The second phase in DCBRP routing protocol is the CHS mechanism. This mechanism is responsible to select one chain head in each cluster in the sensor network. Therefore, there is *N* chain heads in the network that has *N* clusters. At the initial point, the BS will calculate the number of chain heads. It will then compare to find the minimum value of the selection factor (CHS_{factor}). Since CHS_{factor} is the factor that is calculated in a fashion that divides the amount of power consumption of this node by the remaining energy of the same node. Therefore, the CHS mechanism in BS needs to do the following tasks:

1. Receive the remaining energy of all network nodes every round to assign CHs role for the selected nodes;

2. Calculate the CHS_{factor} for every node in the cluster;
3. Compare all node's CHS_{factor} and choose the minimum value (proper node in every cluster to be the chain head); and
4. Broadcast the chain head selection decisions for all sensing nodes.

From the first step at the end of each round, all nodes send their remaining energy to the BS to start CHS_{factor} calculation for all nodes based on its own characteristics and ability for data delivery. The BS will make comparison to obtain the minimum value of CHS_{factor} for all nodes in the same cluster and assign the CH nodes for each cluster in the network. Finally, the BS will broadcast CHS mechanism decisions to all cluster nodes and will wait for the next phase. Where, in routing protocols, when needs to make decision the nodes status should be share, DCBRP doing same things but BS will make the necessary calculations.

The main idea behind the CHS mechanism is to measure nodes' ability by calculating the CHS_{factor}, therefore, applying the impression CH selection such that the CHS mechanism will choose the node which spends minimum amount of energy from its remaining energy to transmit data to the BS:

Power consumption for *k* bit for *d* distance is

$$E_{consumption} = E_{elec} * k + E_{amp} * k * d^2 \tag{4.5}$$

and, $E_{remaining}$ is the remaining energy in every node, k is the number of bits, and d is the distance with BS, so

$$\mathrm{CHS_{factor}} = \frac{\mathrm{E_{consumption}}}{\mathrm{E_{remaining}}}$$ // this is from CHS mechanism requirements, and

$$\mathrm{E_{remaining}} = \mathrm{E_{Initial}} - \sum_{1}^{\mathrm{current\ round}} \mathrm{E_{consumption}} \qquad (4.6)$$

So, from (4.5), and (4.6):

$$\mathrm{CHS_{factor}} = \frac{\mathrm{E_{elec}} * \mathrm{k} + \mathrm{E_{amp}} * \mathrm{k} * \mathrm{d}^2}{E_{Initial} - \sum_{1}^{current\ round} E_{consumption}} \qquad (4.7)$$

where, E_{elec} is the amount of energy consumption for starting the electronic circuit, while E_{amp} is the amount of energy consumption for amplifier in the sensor nodes and $E_{initial}$ is the initial energy for the node in the first time.

By applying Equation 4.7, CHS mechanism is considered a proactive mechanism because it will measure the ability of data delivery for nodes before choosing them. As a result of this behavior, the DCBRP routing protocol will not lose any data during CH node transmitting phase because it would select the strongest node as its chain head role (choosing minimum $\mathrm{CHS_{factor}}$ means that this node will spend minimum energy to deliver network data and it will still live during this round).

Figure 4.4 shows CHS mechanism selects three chain heads for three clusters depending on the number of clusters in the sensor network. Furthermore, this is advanced round number, so nodes 12, 51 and 72 in cluster 1, 2 and 3, respectively, are selected by considering their $\mathrm{CHS_{factor}}$. In addition, they will spend a minimum amount from their energy when they play the chain head role (due to the behaviors of CHS). In addition, $\mathrm{CHS_{factor}}$ will be calculated again by the BS and the role of these nodes would be changed depending on their residual energy.

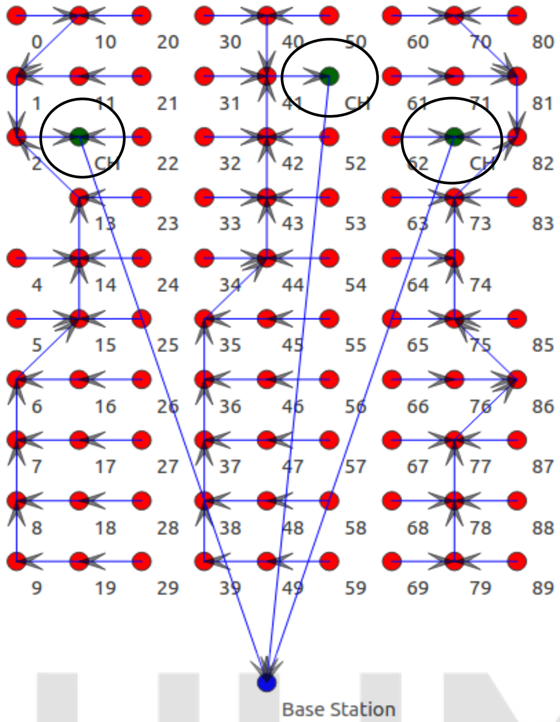


Figure 4.4. CHS Mechanism in DCBRP Routing Protocol

4.3.2 The Implementation of CHS Mechanism

CHS mechanism works in the second phase of DCBRP routing protocol because it needs to know the number of clusters in this network (each cluster has three chains as explained in BCM mechanism) to calculate the number of chain heads. Therefore, the implementation of CHS mechanism in second part of DCBRP protocol is intended to assign the suitable node in every cluster as a chain head. Only CH has direct connection with the BS.

In addition, for the ns-3 simulations, the implementation of chain head selection mechanism means the implementation of Equation 4.7 and connection management of chain heads with the BS. In pre chain head's selection, the distance between every node with the BS can be measured by the signal strength or by distance function in the Static Grid Mobility model, which is already included in ns-3. Figure 4.5 explains the pseudo code of CHS mechanism with all its steps.

In order to enumerate the number of chain head in network, CHS mechanism will receive the number of clusters from the previous mechanism (BCM). Then works to assign one CH for every cluster, which will be responsible to transfer all the nodes' data for this cluster to the BS in this round. Subsequently, ns-3 Mobility model will calculate the distance, i.e., the distance between nodes and the BS (to use it in energy consumption equation). Also TX energy consumption needs to be calculated by focusing on the transmitting energy consumption function as well as the packet size required by BS, distance, and remaining energy to obtain the $CH_{Sfactor}$. Moreover, the BS selects the nodes, which have minimum value of CHS_{factor} to be a chain heads.

Procedure: *ChainHeadsSelection*

NumberOfChainHeads ⟵ *NumberOfClusters*

int ratio[NumberOfChainHeads]

For i=1 to (*NumberOfChainHeads*) ***do***

ratio[i]=EnergyTxNode[i](PacketSize , dist[i]) / Er [i]

For j=1 to (*NumberOfNodesInThisCluster*) ***do***

$$CHS_{factor}[j] = \frac{E_{elec} * k + E_{amp} * k * d^2[j]}{E_{Initial} - \sum_{1}^{current\ round} E_{consumption}\ [j]}$$

If $CHS_{factor}[j] < ratio[i]$ ***then***

{ $ratio[i] = CHS_{factor}[j]$

CHindex = j }

End

CH[i]=CH[CHindex]

Connect (CH[i], BaseStation)

End

End Procedure: *ChainHeadsSelection*

Figure 4.5. Pseudo-code for CHS for DCBRP Routing Protocol

4.3.3 The Verification and Validation of CHS Mechanism

Verification is important step to confirm that CHS has been correctly converted from the pseudo code to programing language. As mentioned in Chapter Three, Eclipse IDE C++ helps to ensure that CHS mechanism implementation is free of bugs and errors when it is programed in C++ Language, as a requirement of ns-3.

While, the validation of CHS consists of two parts: The first one is to monitor Equation 4.7 to ensure similar expected results by using both mathematical and simulation approaches. The second is to test its behavior inside the ns-3 network simulator by monitoring the energy consumption in different rounds, for example, 100, 250, 500 and 700. Next, the second part is to test the CHS mechanism in DCBRP routing protocol for WSN, where it will insert inside the benchmark routing protocol which is PEGASIS to measure the ability of CHS in WSN environment.

4.3.3.1 Validation of CHS_{factor} Equation

CHS_{factor} is considered the main element in this mechanism. Table 4.4 presents five cases for CHS mechanism operations in ns-3 to calculate the CHS_{factor} and obtain the chain head node in the first cluster (30 nodes in one cluster). The chain head selection is based on particular factors, which are shown in Table 4.4 that uses Equation 4.7. This choice means that Node28 is more suitable node in round 100 to function as the chain head role because it spends less energy from its remaining energy to deliver network data to the BS.

Table 4.4

CHS_{factor} Obtained from ns-3 for Different Rounds

Case	**Round no.**	**Remaining Energy**	**Distance with BS**	**Energy Consumption for 1 Packet**	**CHS_{factor}**	**Node ID (CH)**
1	**100**	1.65056	36.0555	0.00036864	0.000223	Node28
2	**250**	1.3015	44.7214	0.000512001	0.000393393	Node27
3	**500**	0.829764	58.3095	0.00079872	0.000963	Node16
4	**750**	0.367199	63.2456	0.000921601	0.002509814	Node25
5	**900**	0.199025	117.047	0.00290816	0.014612034	Node0

Furthermore, mathematical calculation is required in this section to confirm the results obtained from the ns-3 simulation. Data captured from ns-3 network simulator for rounds 100, 250, 500, 750 and 900 will be used to obtain the CHS_{factor} the following calculations:

Case 1:

$E_{remaining}$ = 1.65056 J; E_{elec} = 50 * 10^{-9} J and

E_{amp} = 100 * 10^{-12} J; k=2048 bit; distance (28,BS) = 36.0555 m

$$\mathrm{CHS_{factor}} = \frac{\mathrm{E_{elec}} * \mathrm{k} + \mathrm{E_{amp}} * \mathrm{k} * \mathrm{d}^2}{E_{Initial} - \sum_{0}^{current\ round} E_{consumption}}$$

$$\mathrm{CHS_{factor}} = \frac{50 * 10^{-9} * 2048 + 100^{-12} * 2048 * 36.0555^2}{1.65056}$$

CHS_{factor} = 0.000223

This is the minimum CHS_{factor} in the round number 100, which is Node28. Therefore, this node will function as the chain head for this round. This calculation needs to be repeated for round number 250, 500, 750 and 900, so will get the value of CHS_{factor} which is the same value as shown in the above Table 4.4.

4.3.3.2 Validation of CHS in PEGASIS Protocol

In PEGASIS protocol, CH is selected randomly by using the mod operator between the number of nodes and the current number of round. Thus, it will be in random position in the network to make sure that the first node dies in random position and does not affect the network behavior. While, CHS mechanism chooses the CH depending on the nodes ability measured by CH_{factor}, therefore, CHS mechanism is inserted in standard PEGASIS protocol for validation. The comparison results between standard PEGASIS and PEGASIS-CHS is shown in Table 4.5 and the CH energy consumption metric is used to measure the efficiency of CH selection.

Table 4.5

Validation of CHS inside PEGASIS Protocol

Based on standard PEGASIS	Energy consumption for CH with data fusion scenario	Energy consumption for CH without data fusion scenario
Enhancement of PEGASIS-CHS	60.78%	58.3%

Table 4.5 shows energy consumption percentage enhancement by CH in PEGASIS-CHS as compared to the standard PEGASIS. Moreover, CHS mechanism shows the successful working inside PEGASIS protocol and it is able to reduce the energy consumption by chain heads in both data fusion and without data fusion scenarios. Some CHs in PEGASIS protocol will die during data transmission because it ignores the remaining energy during the CH selection phase. The energy consumption and

remaining energy are used to obtain the CHS_{factor} in PEGASIS-CHS, therefore, it is the key factor for CH selection and will place the CH near to the BS as long as possible. On the other hand, standard PEGASIS uses random way for CH selection which may select CH located far from the BS, while the distance is an important factor in energy consumption equation, therefore it will consume a lot of energy.

4.4 Next Hop Connection Mechanism (NHC)

This chapter presents the Next Hop Connection mechanism (NHC). It is the third mechanism in DCBRP routing protocol. This mechanism helps all sensor nodes to choose the next hop connection carefully by depending on the two important factors, i.e., the remaining energy of the node and distance between the nodes.

During the relevance of the energy constraint in WSN, the routing protocols were designed with much attention to the next hop connection part. In proactive protocols, routing information for all known destinations is maintained up-to-date all the time [121]. The packets forwarding from the source node to destination node (chain head) will depend on this mechanism in peculiar way. In other routing protocols the nodes are dependent on the shortest path, distance, energy, or neighbour method for drawing the packets path. In earlier reflection, the distance between hops has highly priority because most of these protocols used the First Order Radio Model for energy consumption calculations. In this model the squared of distance value can really affect the energy consumption in the transmitting phase.

Furthermore, Greedy algorithm uses only the distance to take decision about which is the next node (hop) for connection. From this perspective, all protocols which use Greedy for data delivery have the same drawback in the packet forwarding because distance is not a sufficient parameter for path selection. Some of these nodes have good distance with poor energy remaining and thus cause data loss when they become the intermediate nodes in the chain.

Figure 4.6 explains the occurrence in routing protocols, which use the Greedy algorithm for next hop connection. The figure below shows the disregard of node's energy, which may cause data loss during the data aggregation phase.

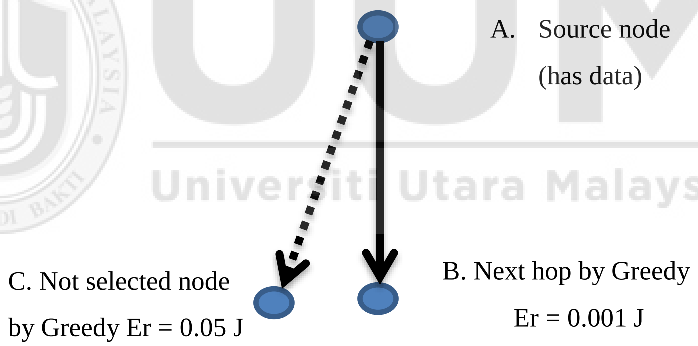


Figure 4.6. The Main Drawback in the Next Hop Connection by Greedy

Additionally, it is good to consider the remaining energy for choosing the next hop connection. However, depending on energy, it is not sufficient without the distance parameters. Shortest path in WSN has been ignored during the energy consumption, i.e., the path with the minimum distance from source node to the destination node that may cause rapid depletion of some of the energy. In other words, the node may have little energy and long distance among specific nodes in the chain, which may be died soon.

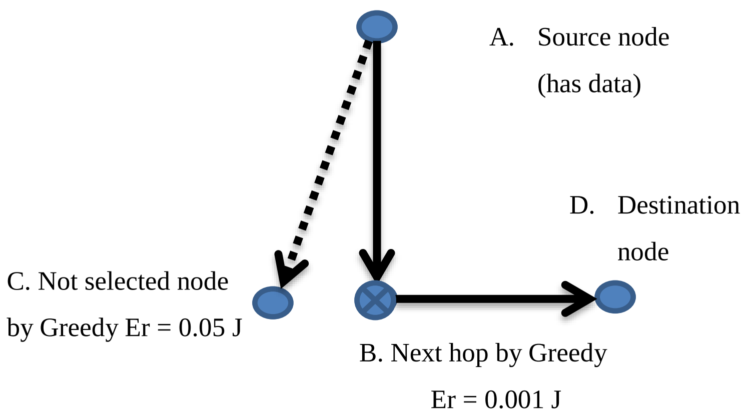


Figure 4.7. The Drawback in Select the Shortest Path in WSN Routing Protocols

Shortest path in WSN is not necessary to be the best choice at all because some time weak node (weak in distance or energy) exists. Figure 4.7 show that node A needs to send its data to node D and selects node B as its next hop node by distance. However, node B has low energy and it will die during transmitting phase and lose all its data.

Therefore, in WSN for all routing protocols, it is necessary to have an efficient mechanism to select the next hop connection. Next Hop Connection mechanism (NHC) maintains both energy and distance for route selection and must be changed during the network lifetime according to changing of energy level in network nodes since the distance factor is constant before the first node die in the network.

4.4.1 The Design of NHC Mechanism

Next Hop Connection mechanism should be designed efficiently to keep the weak nodes out of the main chain in DCBRP routing protocol. In addition, selection of the strongest nodes based on their characteristics helps the node keep away from the early death. Moreover, selecting the strong nodes to be members in the main chain (choosing the proper nodes for next hop) has the following benefits:

1. Selecting the strongest path for the network data;
2. Keeping the weak nodes alive as long as possible for data sensing purpose;
3. Eliminating chain disconnection (link failure) in the main chain; and
4. Increasing the reliability of data delivering

As mention in Chapter Three, the distance is important parameter and it is calculated by the BS and the Mobility Model in ns-3 since all nodes position are fixed from the deterministic nodes deployments method in the sensing area. Furthermore, the BS will receive all nodes information at the end of every round including energy level (remaining of node's energy).

So, for getting the distance between (X_A, Y_A) and (X_B, Y_B):

$$d_{A,B} = \sqrt[2]{(Y_B - Y_A)^2 + (X_B - X_A)^2} \quad (4.8)$$

now, $E_{remaing}$ also needs to be calculated

$$\mathrm{E}_{\mathrm{remaining}} = E_{Initial} - \sum_{1}^{current\ round} E_{consumption} \quad (4.9)$$

In addition, NHC mechanism requirements are

- Node has high Energy
- Node has short distance

So, from (4.8), (4.9) and NHC requirements, the NHC_{factor} should be

$$NHC_{factor} = \frac{E_{Initial} - \sum_{1}^{current\ round} E_{consumption}}{\sqrt[2]{(Y_B - Y_A)^2 + (X_B - X_A)^2}} \quad (4.10)$$

where, $E_{Initial}$ is the initial energy of the nodes, $E_{consumption}$ is the energy consumption for all the previous rounds, NHC_{factor} is the comparison factor for NHC mechanism to the next hop selection mechanism, X_A,Y_A is a position of node A and X_B,Y_B is a position of node B. Node A needs to obtain NHC_{factor} with node B to be compared with others.

In addition, in every network level (row), corresponding node needs to find the next hop node before its data collection session to guarantee delivering of sensing data to the BS. To make efficient selection, the node has short distance with high energy level will be in the main chain in each cluster. In other words, the comparison will depend on NHC_{factor} only, i.e., the node which has maximum value will be the next hop for this network level.

NHC mechanism can improve the data routing and prolong the network lifetime by keeping the sensor node life as long as possible. For example, in Figure 4.8, node A needs to select next hop connection. It is clear if node A selects the next hop connection by energy, it will be connected with node D or B if it prefers the distance more than energy parameter. In addition, it will be connected with C if the DCBRP routing protocol is applied, as explained in Table 4.6.

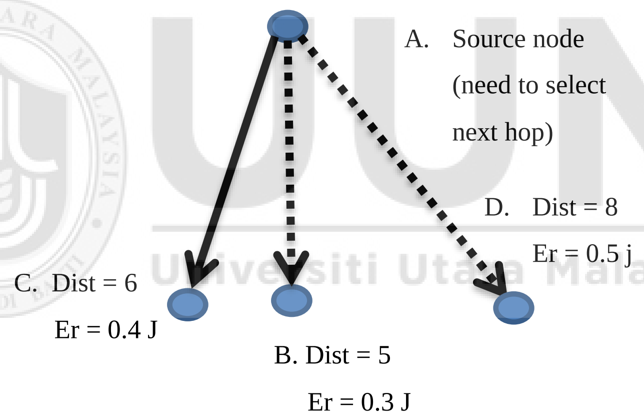


Figure 4.8. Selecting the Next Hop by NHC_{factor} in DCBRP protocol

According to Table 4.6, node A has to select the next hop connection by efficient way to prevent the link failure. It also needs to confirm the data delivery without any packet loss because if the node dies early in the round, the network must wait for the next round to repair the data routing during the next hop connection mechanism.

Furthermore, in DCBRP routing protocol NHC mechanism will work from various levels to choose the next node within the following level only.

Table 4.6

The Difference of Next Hop Selection's strategies

Node	**Emerge Remaining**	**Distance**	**NHC_{factor}**	**Next Hop Connection**
B	0.3	5	0.0600	Shortest
C	0.4	6	0.0660	NHC_{factor}
D	0.5	8	0.0625	Energy

In other words, Figure 4.9 shows the NHC mechanism in different rounds and how it changes the link connection from time to time to prolong the network lifetime. Therefore, the sensing area will still be guarded by keeping the weak nodes (i.e., the node which has low energy) for sensing purpose only. The primary concern here is to maintain the node with low level out of the main chain to save its energy for sensing purpose only. This mechanism will increase the energy balancing between the nodes for prolonging the network lifetime in WSN.

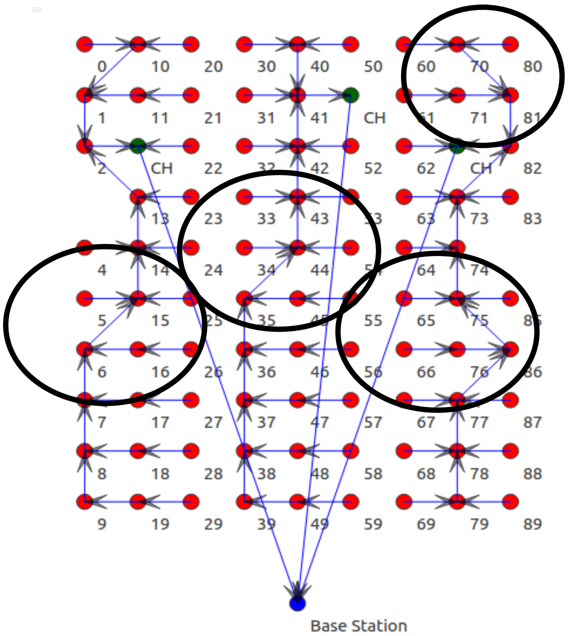


Figure 4.9. The Connection Changed by NHC Mechanism

Figure 4.9 shows the impact of NHC mechanism for changing the packets route or nodes connection in chain-based routing. The route changing will be in the early round to prepare for packets travelling from source nodes to the network base station. NHC_{factor} plays an important role for next hop connection decisions. Therefore, node 7 in the above Figure selects node 6 as a NHC, while node 6 selects node 15 (not 5) depending on its remaining energy and distance (same thing for node 35, 77, 70 and others). However, it is also important to note here that everywhere in the sensing area NHC mechanism chooses the strongest node from each row (three nodes) to build robust main chain in every cluster. Furthermore, NHC mechanism will recalculate the network path in every round for three reasons:

1. Preventing the weak nodes to join the main chain;

2. Saving energy in the weak nodes for sensing purpose; and

3. Making the important energy balancing between the nodes.

4.4.2 The Implementation of NHC Mechanism

The NHC is the third mechanism in the DCBRP routing protocol and it plays an important role to prolong the network lifetime depending on the distance and energy parameters. Therefore, the implementation of NHC should satisfy the developer's design and the mechanism requirements such as,

1. All necessary calculation made by the Network base station;

2. All NHC_{factor} will be in small chain level (horizontal level)

3. Keeping all NHC_{factor} update (recalculated in every round)

The implementation of NHC mechanism in ns-3 is started when the DCBRP routing protocol finishes the BCM and CHS mechanisms implementation. The BS has all the information about the network's nodes. It will receive this information at the end of each round and make all calculations for BCM, CHS, and NHC mechanisms together and broadcast the decisions to all nodes before the nodes sensing of data.

Figure 4.10 presents pseudo code of the Next Hop Connection mechanism, in the first time procedure needs to know the number of clusters from BCM mechanism to build the first loop. The next loop will depend on the number of rows in the network to select next hop for all rows in the cluster. The initial ratio should be there to begin the factor comparison. Last loop will be based on number of columns to assign the NHC_{factor} to the strongest node in this row.

Procedure: *NextHopConnection*
  Receive NumberOfClusters
  For i=1 to (*NumberOfClusters)* ***do***
    For j=1 **to** (*NumberOfRows)* ***do***
      ratio[j]= Er [j] / dist[j]
      For f=1 **to** *(NumberOfColumnsInCluster)*

$$NHC_{factor}[f] = \frac{E_{Initial} - \sum_{1}^{current\ round} E_{consumption}\ [f]}{\sqrt[2]{(Y_B - Y_A)^2 + (X_B - X_A)^2}}$$

        If *NHC_{factor}[f] < ratio[i]* ***then***
        { CHS_{factor}[f] =ratio[i]
          NHCindex = f }
        End
      Connect *(Node[A], Node[NHCindex]*
    End
  End
End Procedure: *NextHopConnection*

Figure 4.10. Pseudo-code of NHC in DCBRP Routing Protocol

4.4.3 The Verification and Validation of NHC Mechanism

The verification step is coming to confirm that NHC mechanism is correctly programed based on main idea of them. This mechanism is designed in previous section to transfer the pseudo codes or the flowcharts to the C++ language for real compatibility with ns-3 network simulator. For this purpose, Eclipse IDE C++ uses instance of normal text editor because it has no syntax errors indicator, predictable function's word, or alignments of the programme.

As a result of using Eclipse for NHC mechanism programming, the verification step is completed by confirmation that it had been programmed correctly and is free of errors and bugs. This requirement is important to make NHC mechanism compatible with other parts of the DCBRP routing protocol and made ready to test the validation of these mechanism.

Next Hop Connection mechanism (NHC) plays an important role to keep the chain link away from failure during data transmission phase. The validation of NHC mechanism consists of two parts: First is to validate the NHC_{factor} Equation and second to validate the behaviour of NHC mechanism in the WSN simulation.

4.4.3.1 Validation of NHC_{factor} Equation

In this section, NHC_{factor} needs to be obtained by two methods to ensure its functionality and able to satisfy the designer requirements. This task is completed by examining the NHC_{factor} value of round number 898 (in without data fusion scenario) link changed probability in the network topology listed in the following Table 4.7:

Table 4.7

Next Hop Connection for Node11

Node11 needs NHC	Round no.	Nodes may be NHC	Remaining Energy	Distance with Node11	NHC_{factor}	NHC Node
1		Node2	0.126059	14.14214	**0.008914**	
2	898	Node12	0.084183	10.00000	0.008418	***Node2***
3		Node22	0.101448	14.14214	0.007173	

According to Table 4.7 values obtained from ns-3 network simulator environment, the BS needs to select NHC for Node11, therefore, it will apply the NHC mechanism. To validate the simulation results, Equation 4.10 will calculate NHC_{factor} mathematically by using same case and compare both results.

$E_{remaining}$ (Node2) = 0.126059; $E_{remaining}$ (Node12) = 0.084183;

$E_{remaining}$ (Node22) = 0.101448 , distance (11,2) = 14.14214, distance (11,12) = 10 ;

distance (11,22) = 14.14214

$$NHC_{factor} = \frac{E_{Initial} - \sum_{1}^{crnt\ rd} E_{cons}}{\sqrt[2]{(Y_B - Y_A)^2 + (X_B - X_A)^2}}$$

Option 1*Node2*: $NHC_{factor} = \frac{0.126059}{14.14214} = \mathbf{0.008914}$

Option 2 *Node12*: $NHC_{factor} = \frac{0.084183}{10} = 0.008418$

Option 3 *Node22*: $NHC_{factor} = \frac{0.101448}{14.14214} = 0.007173$

From the above case, result shows exactly similar value of NHC_{factor} between simulation environment and mathematical equation results. For now, Equation 4.10 shows its ability to compare the factor for next hop selection in different energy and distance values.

4.4.3.2 Validation of NHC in PEGASIS Protocol

In this section, Next Hop Connection Mechanism (NHC) needs to be applied within the WSN routing protocol to ensure that this is applicable for WSN simulation environment. Therefore, Equation 4.10 and all additional programming parts should work together to provide efficiency to the NHC mechanism. Table 4.8 presents the different amount of enhancement of PEGASIS-NHC as compared to the PEGASIS protocol in terms of total nodes energy consumption in data fusion and without data fusion scenarios.

Table 4.8

Validation of NHC inside PEGASIS Protocol

Based on standard PEGASIS	Energy consumption with data fusion scenario	Energy consumption without data fusion scenario
Enhancement of PEGASIS-NHC	30.19%	73.54%

When node depletes its energy, it will die and will not be able to sense or forward any data to the previous node (immediate node). The NHC mechanism plays an important role to eliminate the weak node (has little energy) from the main chain in every cluster. Depending on NHC_{factor}, the BS will avoid early death of node by maintaining the weak nodes to perform the sensing task only. Furthermore, energy consumption is an important metric for all sensor nodes to extend the network life and increase the sensing rounds, as shows in Table 4.8. To sum up, the NHC is successfully inserted in PEGASIS protocol and is effective for the power consumption in both scenarios.

4.5 Summary

This chapter presents DCBRP routing protocol through its three mechanisms which are Backbone Construction Mechanism (BCM), Chain Head Selection mechanism (CHS) and Next Hop Connection mechanism (NHC). BCM considers a first phase in DCBRP routing protocol and it is responsible to reduce the delay caused by long or/and single chain by dividing the network to specific number of clusters and build the chains. CHS mechanism is responsible for selecting the chain head node in each cluster in the network. This selection depends on the ability of nodes, in other words, CHS_{factor} measures the ability of nodes to deliver network's data with minimum energy consumption from its remaining energy. Node that has minimum CHS_{factor} will be selected by BS to be the CH for this round. While NHC mechanism is responsible to select the next hop connection for every row chain in the network. This mechanism depends on NHC_{factor}. It is obtained from dividing the remaining energy by distance between nodes. The node that has the maximum value of NHC_{factor} will become the next hop connection for this row in this round. The NHC mechanism has the greatest potential to extend the network lifetime for sensing node because it keeps the weak node out from main chain to avoid the link failure and data loss. Consequently, this chapter has the design, implementation, verification and validation of three proposed mechanisms (BCM, CHS and NHC). Furthermore, the performance of DCBRP will be evaluated with existing routing protocols in WSN in the next chapter.

CHAPTER FIVE
DCBRP PERFORMANCE EVALUATIONS

5.1 Introduction

DCBRP routing protocol mechanisms were discussed in details in previous chapter, while their performance evaluation is presented in this chapter. For comprehensive evaluation, the chapter starts with data fusion scenario in Section 5.1, Section 5.2.1 presents the evaluation of DCBRP in terms of network lifetime, Section 5.2.2 discusses energy consumption, Section 5.2.3 presents the end-to-end delay and Section 5.2.4 deals with energy*delay metric. Section 5.3 is concerned with the evaluation of DCBRP, TSCP and CCM without data fusion in terms of network lifetime, energy consumption, end-to-end delay, and energy*delay in Section 5.3.1, 5.3.2, 5.3.3, and 5.3.4, respectively. Finally, the chapter is concluded with its summary presented in Section 5.4.

5.2 Evaluation of DCBRP with Data Fusion Scenario

Sensor nodes may generate redundant data therefore data aggregation is applied to prevent the duplication of same data and decrease the number of packet transmission. The aggregation (fusion) of data is a combination of packets that are collected from different nodes and put together to decrease the number of packet and its size [154]. Data fusing techniques are very efficient to increase the lifetime in WSN, especially when multi hop routing is applied in the network. However, data fusion may not be considered when designing a new routing protocol to study the behaviour of packets traveling from source to destination.

Data fusion is the process of combining n packets with size k and the result is one packet of size k instead of one packet of size *nk* [70]. Depending on the data fusion energy consumption which is presented in [27], the cost of energy for data aggregation is 5 nJ/bit, whereas, Equation 5.1 calculates the amount of energy consumption for data fusion.

$$E_{fusion}(k) = E_{fn} * k \tag{5.1}$$

where, E_{fusion} means the energy consumption of data fusion for k-bit per packet, E_{fn} is the energy consumption of fusing 1-bit message.

5.2.1 Network Lifetime

Network lifetime of the node refers to the round where the node will spend all its energy, therefore, the node is considered as die and it is out of service (i.e., not sensing and transmitting data). In other words, it is considered as to which round the network loses its 1st node, 10%, 25%, 50% and 100% (LND). Therefore, this is thought as an important metric to measure the ability of DCBRP routing protocol to extend the network sensing rounds. A dead node means that the network loses one of the routing options and makes the upper and lower nodes suffering from long distance connection and loses some sensing coverage.

Figure 5.1 shows the network lifetime of the DCBRP, TSCP and CCM protocols with employing data fusion. Thus every node will consume E_f energy to fuse neighbor's data with its data and forward to the next and so on. This figure shows that DCBRP extends the node's lifetime successfully because of the behavior of its mechanisms which are BCM, CHS and NHC. The impact of NHC mechanism is to prevent the weak node (has low energy) to join the main chain to keep its energy for sensing purpose only. Furthermore, CHS mechanism will not choose any weak node as CH in any round because of its CHS_{factor} behavior, where it will select the node that spends minimum from its energy. Consequently, the lifetime of network nodes is extended as long as possible.

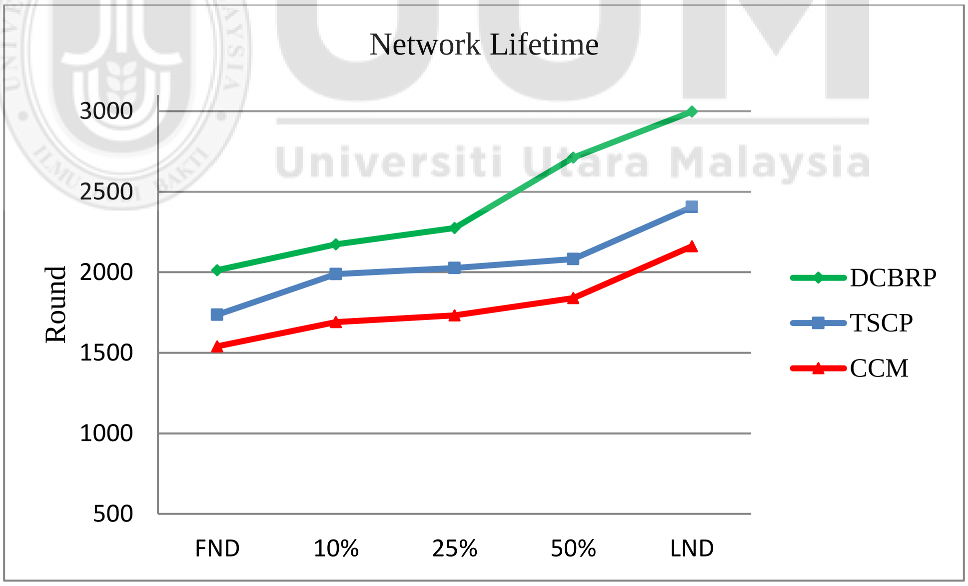


Figure 5.1. Network Lifetime of DCBRP with Data fusion

Furthermore, TSCP protocol has better performance than CCM protocol during the network lifetime metric because of its behavior when CHs send their data only to the neighbor nodes. While, all CHs in CCM protocol send their data to single CH (main head), therefore, they will suffer from long distance and hence shorten the network lifetime. Sequential way in CCM and TSCP for selecting the CHs compels the weak node compulsory to join the main chain and it makes this node die faster than others. Furthermore, Figure 5.1 also shows the significant outperformance of DCBRP routing protocol over TSCP and CCM in terms of stability by 13.7% and 23.5%, respectively (network stability refers to FND [155]). While, the DCBRP protocol enhances the lifetime of nodes by 23.2% and 32.16%, whereas this ratio is 19.7% and 29.7%, respectively, in terms of LND as compared to TSCP and CCM. Thus, DCBRP outperforms the TSCP and CCM with respect to network lifetime and successfully keeps the nodes for sensing data as long as possible.

5.2.2 Energy Consumption

The energy consumption is considered a very important metric in WSN because of the limitation of power supplier for the sensor nodes. In this section the ability of DCBRP routing protocol is measured to save the node's energy during the network lifetime. The Chain-based approach has important advantage to save the energy by applying the concept of chain, where every node is connected only with neighbor to reduce the connection distance, which is considered an important parameter in energy equation (First Order Radio Model).

Figure 5.2 presents the energy consumption of all sensor nodes until the FND for the first protocol. The consumption of DCBRP behavior in the first 1000 rounds was smooth and had small changes because of: firstly, every node is connected with only neighbor by small connection distance through BCM mechanism; secondly, CHS mechanism selects the nearest node as CH at the first time because of its CHS_{factor} behavior, therefore, CHS consumed little energy as compared to TSCP and CCM.

In addition, the border nodes in each cluster in DCBRP protocol are responsible for sensing and thus send data to the neighbor nodes only (which are the left and right columns). Therefore, they do not spend any energy for fusing or receiving data from neighbor until this node becomes NH for the upper or lower rows. While, TSCP and CCM have only one column in the right and one in the left as border nodes, all the rest nodes will consume energy for sensing, receiving, sending, and fusing.

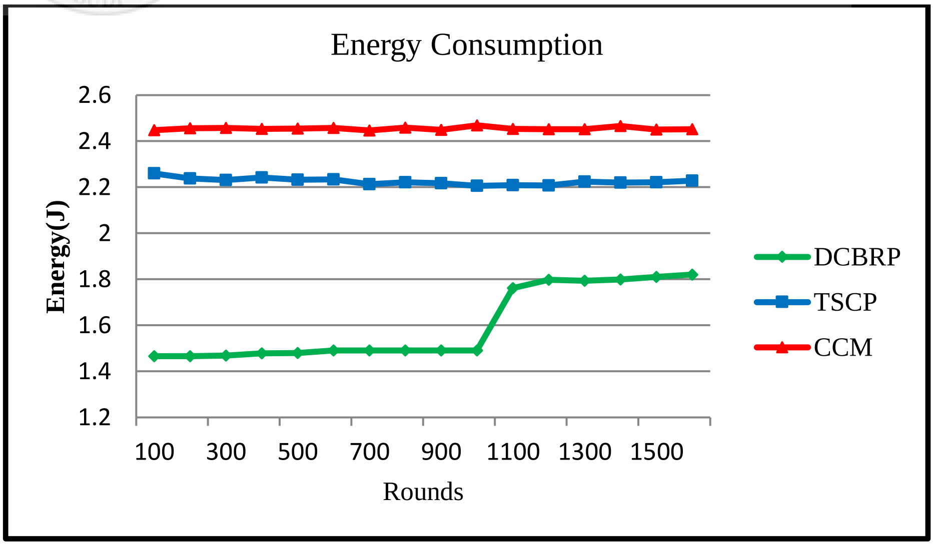


Figure 5.2. Energy Consumption of DCBRP, TSCP and CCM

TSCP has advantage of CCM because it applies the chain concept on the main chain also (chain of CH), therefore it saves the CH energy. On the other hand, in CCM, all CHs spend more energy to transmit their data to the main node during the cluster based approach in every round, especially if the main node is on the border. Figure 5.3 exhibits the remaining energy of DCBRP, TSCP and CCM during the network lifetime until LND. DCBRP shows its priority to save the nodes' remaining energy as long as possible, where there is reverse relationship between the energy consumption and remaining energy.

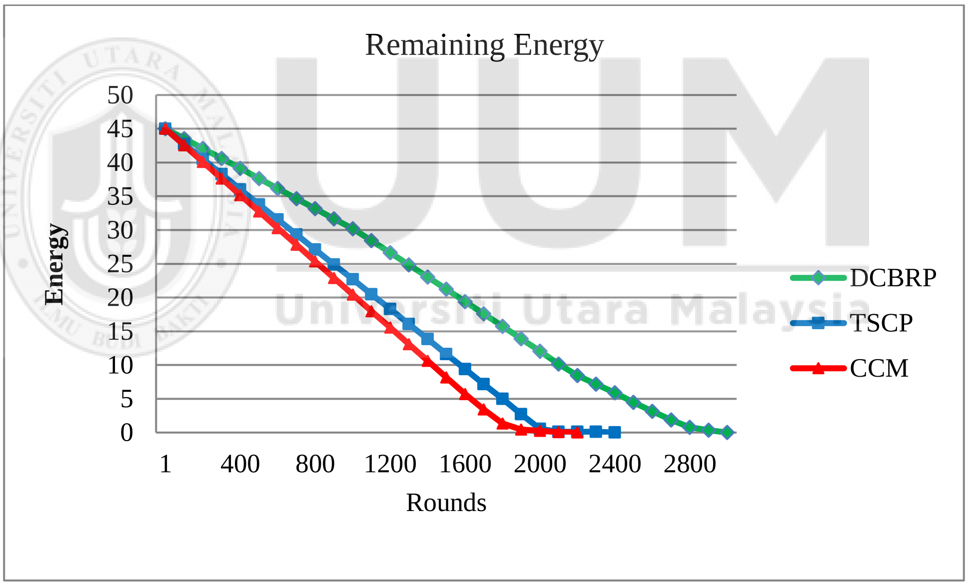


Figure 5.3. Remaining Energy for all nodes in DCBRP, TSCP and CCM

Figure 5.4 illustrates the average energy consumption for all nodes per round until the LND. DCBRP has advantage over both other protocols as it spends approximately 0.01502 Joule in each round for all nodes to complete all data transmission from source to destination. Whereas TSCP needs 0.01871 Joule to transmit all the network data to BS and CCM requires 0.02082 Joule to deliver all the nodes' packets to BS for each round until LND. DCBRP consumes less energy than TSCP and CCM because of the behavior of BCM and CHS mechanism. Furthermore, CCM spends more energy than TSCP during the time of clustering between CHs.

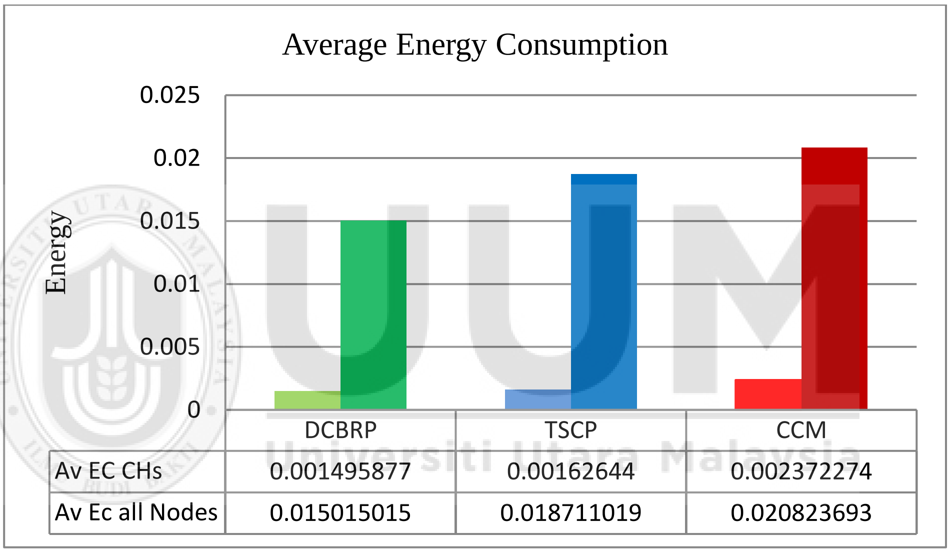


Figure 5.4. Average Energy Consumption in DCBRP, TSCP and CCM

In addition, Figure 5.4 shows the average of CHs energy consumption for DCBRP, TSCP and CCM protocols until FND. Even the DCBRP has three chain heads, CHs will stuck with nodes having low CHS_{factor} which consume little from their total energy. In this situation, the CH role will go to other nodes which also have low CHS_{factor}. TSCP protocol spends 0.00145 Joule in each round for main head only which is selected based on the remaining energy. This behaviour is the same for

CCM also which selects main head by the remaining energy. However, TSCP outperforms CCM where the number of receiving packets in each round equals the number of horizontal chains in CCM while it is only four packets in TSCP protocol, and the same condition befalls for data fusion energy consumption. Furthermore, the behaviour of BCM and CHS significantly reduces the energy consumption of CH nodes in DCBRP protocol, which is 8.03% and 37%, respectively, as compared to TSCP and CCM.

5.2.3 End-to-End Delay

The Chain-based approach has important drawback in delay because all protocols apply the multi hop concept, which introduces more delay. Therefore it is important to measure the end-to-end delay when designing a new routing protocol. Figure 5.5 illustrates the average end-to-end delay happen per packet every 100 rounds until FND. BCM mechanism plays the main role for reducing delay because it minimizes the number of hops for each packet by dividing the network in clusters. Moreover, CHS mechanism selects CH for each cluster, therefore, multi getaway for the network will also contribute to reduce the bottleneck problem.

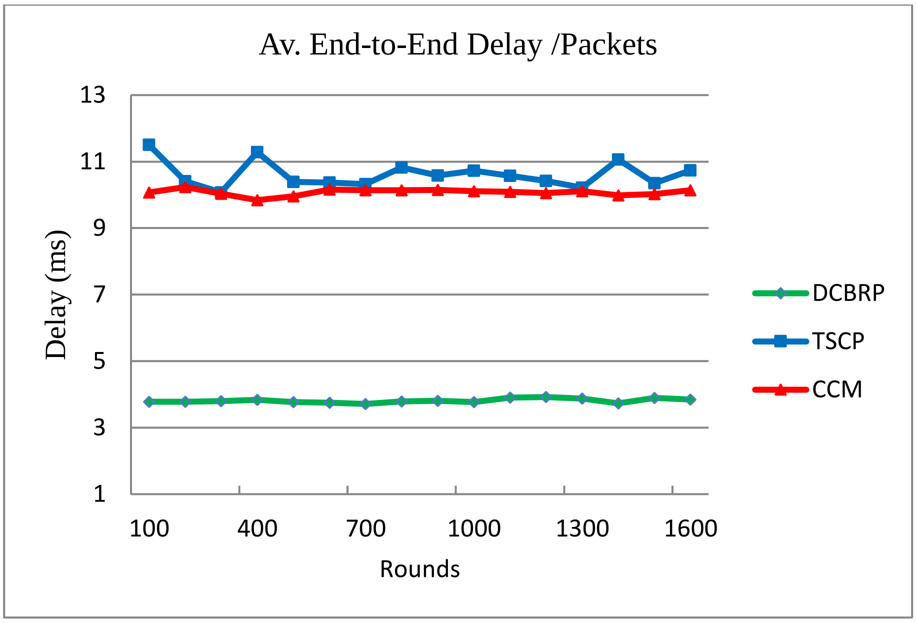


Figure 5.5. Average End-to-End Delay for DCBRP, TSCP and CCM (FND)

DCBRP successfully reduces the overall average end-to-end delay until LND by 65.06% and 63.55% in comparison with TSCP and CCM protocols, respectively, as shown in Figure 5.6. As mention in Chapter Two, the delay can be affected by the number of chain heads, the length of chain, and the number of chains in the network, and all of these factors are related with the protocol design.

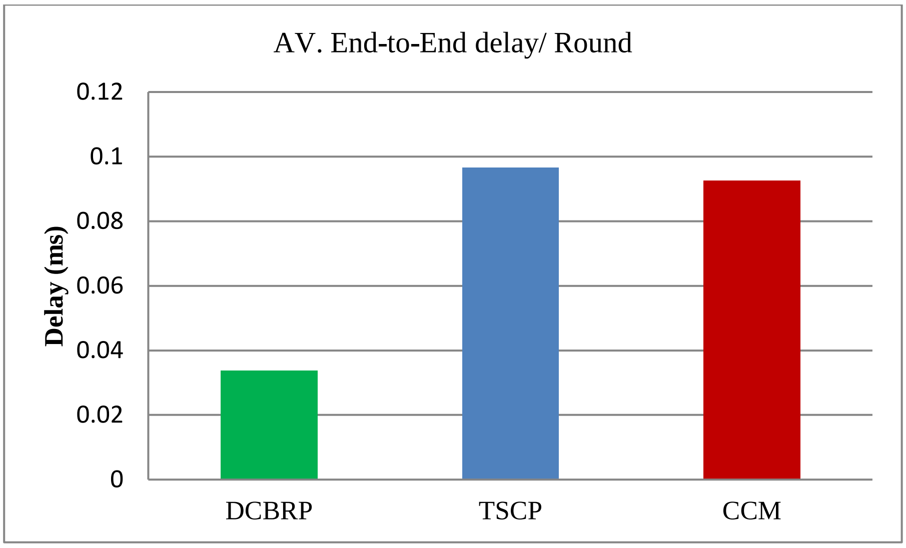


Figure 5.6. Average End-to-End Delay for DCBRP, TSCP and CCM (LND)

The CHs in CCM routing protocol deliver their data to the main head in single hop method and then the main head transfer it to the BS directly. Consequently, the TSCP is outperformed by DCBRP in end-to-end delay because TSCP constructs another chain for CHs and thus the delay is increased during the data redundancy. DCBRB routing protocol applies the multi chain concept with multi CHs to overcome the delay problem in Chain-based approach. Simulation results show that DCBRP has smooth behaviour of delay during the network lifetime and it successfully outperform TSCP and CCM with regards to end-to-end delay

5.2.4 Energy*Delay Metric

Lindsey in [27] proposed Energy*Delay metric to calculate the effectiveness of using Chain-based approach on the performance of her protocol (PEGASIS). Chain-based protocol has important tradeoff between energy consumption and delay, in the other words, for fair comparison between protocols' performance, this metric should be considered and calculated. Figure 5.7 illustrates the Energy*Delay metric until FND. As DCBRP shows good performance because of its behavior in the energy consumption and end-to-end delay, the multiplication between them will also be good.

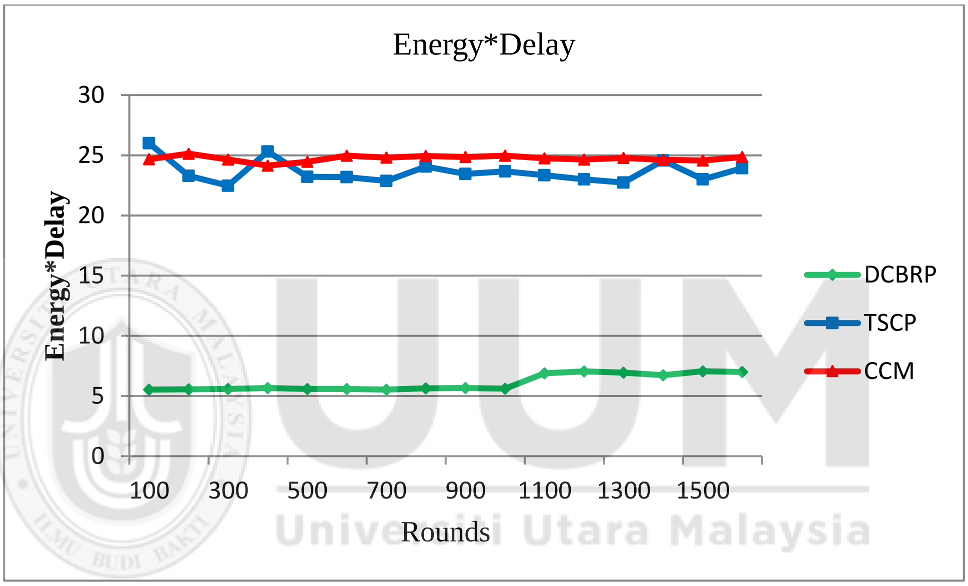


Figure 5.7. Energy*Delay for DCBRP, TSCP and CCM

Moreover, TSCP protocol has some limitations in delay metric but has good performance in energy consumption as compared to CCM protocol. Consequently, TSCP outperforms CCM in terms of Energy*Delay metric and this can exhibit the overall behavior of the protocol. Moreover, DCBRP outperforms both TSCP and CCM in terms of Energy*Delay until LND, as shows in Figure 5.8, which represents the amount of improvement by 74.18% and 75.33 over TSCP and CCM, respectively.

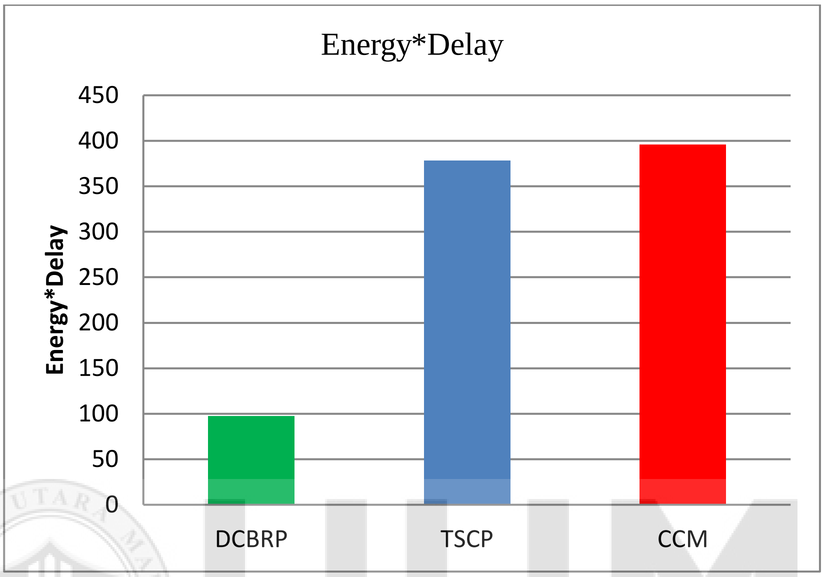


Figure 5.8. Overall Energy*Delay for DCBRP, TSCP and CCM

5.3 Evaluation of DCBRP without Data Fusion

For comprehensive performance evaluation of DCPRB routing protocol, another scenario is deployed as mentioned in Chapter Three. Same metrics are used to evaluate DCBRP routing protocol without data fusion for all nodes. The fusion energy (E_f = 5 nJ/bit) is not applied, therefore every node (which receives one packet) will send two packets (second is own packet). As a result, the nodes will suffer from data redundancy and spend a lot of their energy to deliver data especially to the chain heads and main head. Hence, the evaluation without data fusion has advantage to measure the ability of routing protocols in dealing with large number of packets and keeping the network alive as long as possible for sensing purpose.

5.3.1 Network Lifetime

Due to the energy limitation of the nodes in WSN, the extension of the network lifetime is one of the primary objectives of routing protocols' designer. This research elicits the lifetime of all nodes and offers all the parameters (that have negative or positive affect) and mechanisms to extend the network lifetime without trade-off with others performance metrics.

Figure 5.9 presents the network lifetime for DCBRP, TSCP, and CCM routing protocols in terms of FND 10%, 25%, 50%, and LND for the network nodes. The sensor node dies when it depletes all of its energy during transmitting and receiving data. The NHC mechanism plays an important role to prolong the lifetime of the sensor nodes depending on the parameters for selecting the next hop in every row in the network.

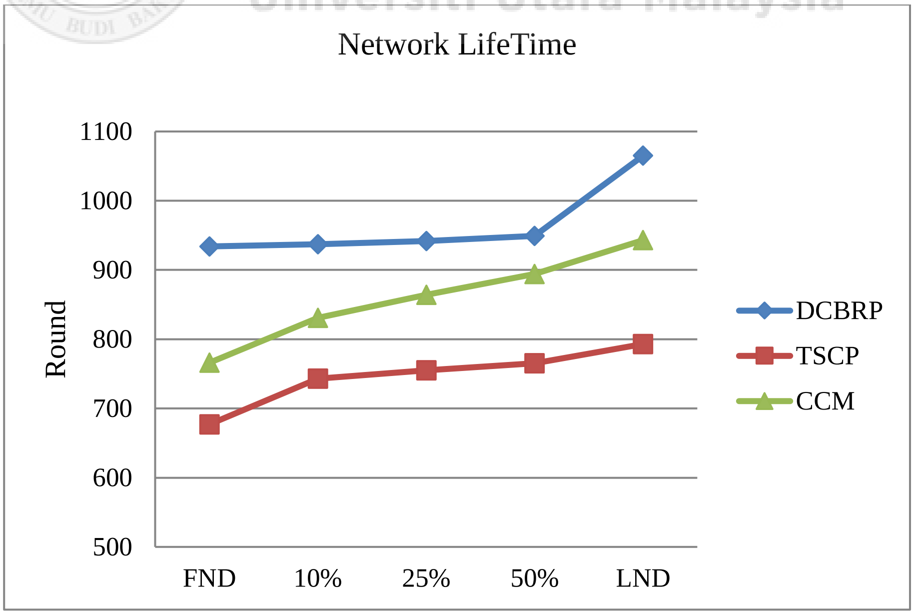


Figure 5.9. The Network Lifetime for DCBRP, TSCP and CCM

According to Figure 5.9, DCBRP routing protocol successfully extends the network lifetime since all protocols start with same energy level. The impact of routing behavior directly affects the network lifetime because all protocol mechanisms work together to reduce the energy consumption in the First Order Radio Model. This model has important parameter, i.e., distance, and it is considered by BCM, CHS, and NHC mechanisms.

The primary finding that can be concluded from the FND is the ability of the routing protocol to keep all nodes having an extended live. Evidently, when the first node dies, the network loses one of its routing options and this leads the upper and lower nodes to spend more energy for delivering their data. Hence, DCBRP routing protocol prevents early dying and this is the main task of the third mechanism in the DCBRP routing protocol, which is the NHC mechanism. As NHC mechanism avoids the weak nodes to be in the main chain, it performs only the sensing task. The CCM and TSCP depend on the sequence method for selecting the next hop connection node, therefore the weak nodes may become a part of the chain and they will die early than other nodes and lose the sensing coverage area.

5.3.2 Energy consumption

The energy consumption is considered one of the most important metrics that should be calculated when designing mechanism or routing protocol for WSN. Therefore, energy consumption is one of the critical issues that needs to be computed, studied, evaluated, and discussed in details to ensure that the DCBRP routing protocol can significantly reduce the energy consumption in different perspective. In addition, it is also worthy to discuss and elaborate that how the network lifetime can be prolonged and the CH energy consumption can be minimized. Therefore, in this section the evaluation of energy consumption for DCBRP, TSCP and CCM routing protocols without data fusion is done for:

A. *All sensor nodes Energy consumption per round*: to measure the behavior of the protocols in terms of energy consumption.
B. *Average energy consumption by the nodes in rounds*: to study that how the reduction of energy consumption can prolong the network lifetime.
C. *Average energy consumption by CHs in the network*: This is relevant to the number of CHs and the selection of CHs as CHS mechanism has side effect when increasing the number of CHs.

Figure 5.10 explains the energy consumption by all nodes within DCBRP, TSCP and CCM routing protocols until FND. In this figure, DCBRP shows stable and smooth behaviors from early rounds until round number 600. CHS mechanism selects the CHs based on the ability of the nodes. It selects the same node until the comparative factor CHS_{factor} selects another node in close distance with the previous CH. For this reason, the DCBRP network seems more stable compared with CCM and TSCP protocols. Additionally, BCM mechanism in DCBRP routing protocol helps to connect the normal nodes only with their neighbors. Therefore, it will not spend energy for delivering data from other nodes and able to keep their energy for sensing purpose for a longer time.

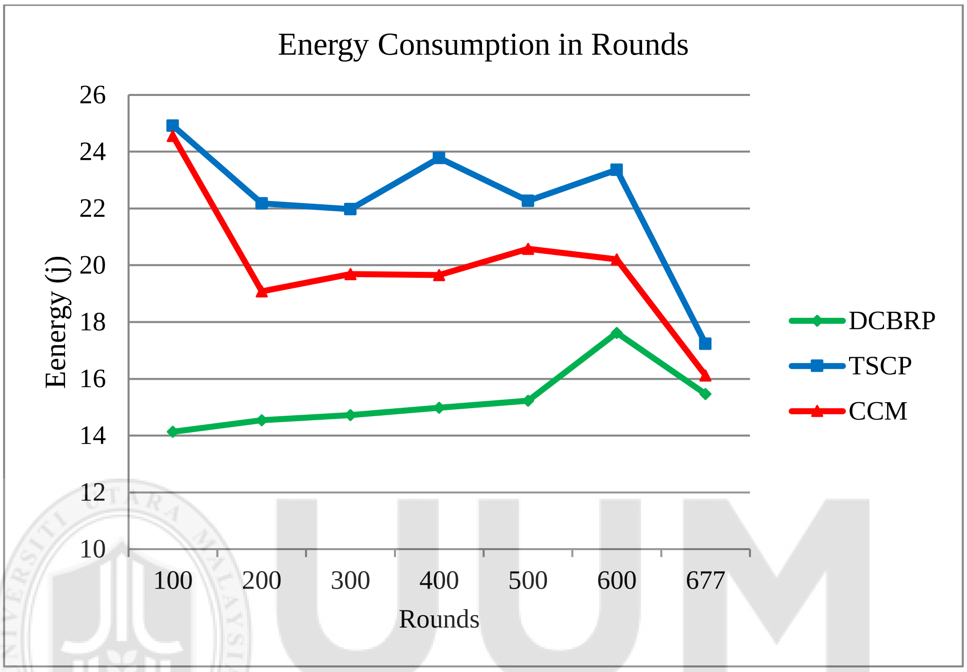


Figure 5.10. Energy Consumption for DCBRP, TCSP and CCM

TSCP selects the CH nodes by sequence method and the main node by the remaining energy only. Therefore, it may select node which has long distance with BS as a main node. Even though the node may have high energy but will spend a lot of its energy in this round. Furthermore, TSCP constructs the normal nodes chain by distance only (CHs also). Therefore, long chain will have negative effect since the nodes spend a lot of energy for data redundancy until reach the main head. While CCM uses the same method in the first phase and it has different CHs connection method, which uses the cluster method to reduce the data redundancy among the

CHs. As a result, it offers more energy saving in comparison with TSCP. Therefore, the fluctuations behavior is very much dependent on the main head position in the network.

Figure 5.11 presents the average energy consumption per round until LND. The figure shows that DCBRP outperforms both TSCP and CCM in terms of average energy consumption in every round during network lifetime. It means that DCBRP successfully reduces the energy depleted by its mechanisms, where BCM builds the backbone chains, and CHS mechanism selects the chain heads depending on CHS_{factor}.

DCBRP has compatible mechanisms work together to reduce energy consumption. Therefore, when DCBRP's node spends 0.17 Joule in each round, it provides good indication that the energy can be saved for the next rounds and the nodes still live for sensing data. TSCP still suffers from dissipating more energy than CCM because the chain of CHs nodes forwards a lot of packets as compared with CCM.

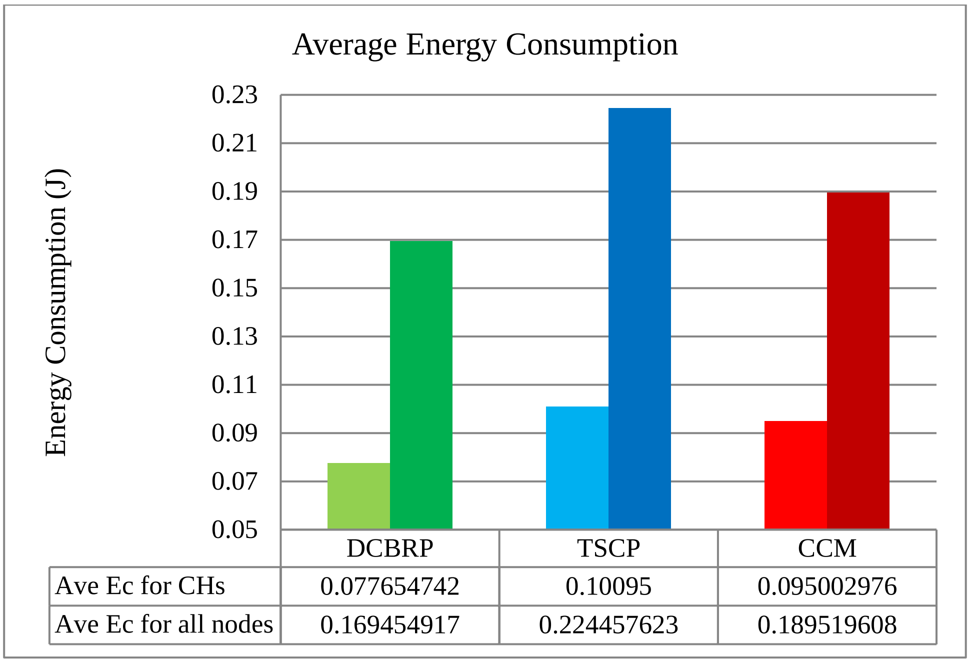


Figure 5.11. Average Energy Consumption for all Nodes and CHs nodes

Finally, average energy consumption for CHs is very critical issue because DCBRP has more CHs in the network while CCM and TSCP have only one CH in their networks. Therefore, CHs energy consumption offers a difficult challenge in the protocols' comparison. However, DCBRP outperforms both protocols in terms of average CHs energy consumption even though it has three CHs. This is because of the CHS mechanism when it assigns the number of CH equal to the number of clusters in the network. It further divides the network load on CHs to provide more energy saving. As CCM and TSCP make heavy load on one main head node without considering the distance factor, it may have long distance with BS.

The summation of average energy consumption for DCBRP is 0.077 joule, while it is 0.1 joule and 0.95 joule for TSCP and CCM routing protocols, respectively.

Therefore, DCBRP can deliver all the network data to the BS with energy consumption balancing between CHs nodes. In other words, the network packets' load on the main head in the CCM and TSCP is divided on the number of CHs in DCBRP.

5.3.3 End-to-End Delay

Delay comes from long chain, which is considered the first problem adopted by this research, and the BCM is proposed in the first objective to reduce the delay. Therefore, the summation of end-to-end delay for all packets needs to be calculated and divided by the total number that are transmitted in this round, as mention in Chapter Three. Furthermore, end-to-end delay should be calculated to satisfy the confidant level. Therefore, *FlowMonitoring* class is used for this task which deals with the iteration in every round for all nodes to make the necessary calculations.

Figure 5.12 presents the End-to-End delay for every 100 rounds until FND for the first protocol (the fluctuation behavior if measured every round). The average delay provides performance behaviors of all protocols which deal with all nodes in the network, where the first dead node can affect the packet path from source to distention. As a result, it is better to provide more fairness for all protocols to measure the delay when all nodes are alive.

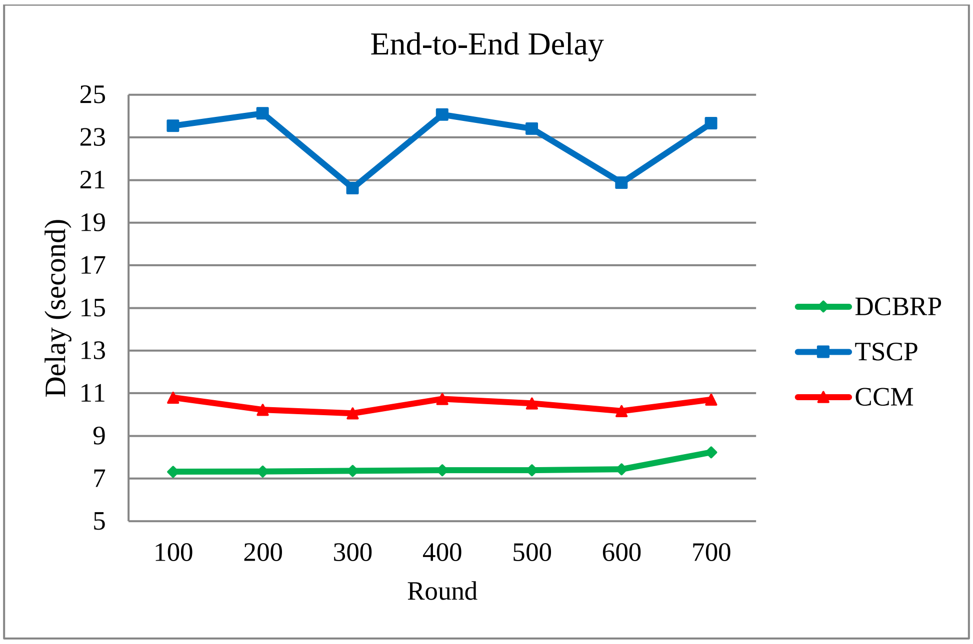


Figure 5.12. Average End-to-End Delay for DCBRP, TSCP and CCM (FND)

Figure 5.12 shows that DCBRP routing protocol outperforms both CCM and TSCP routing protocols in terms of delay, which is affected by the number of chains in the network, long chains, the number of chain heads, and chain heads connections (how CHs will communicate with each other or with the BS).

Additionally, DCBRP reduces the number of chains and the long chains by applying BCM mechanism, which selects specific number of clusters (backbone chains) from its Equations. CCM and TSCP apply the same method when assigning one chain for every row in the network. It also depends on the width of the network, which will construct multiple chains and then increase the transmission time for the packets from source to the BS.

The number of clusters needs the network to assign more chain head which should be calculated by CHS mechanism. The delay will decrease when the number of network's getaways increases during the network load, which will be dividing on all CHs nodes. CCM and TSCP have only one main node which is responsible to deliver all network packets to the BS and it is affected by long queue.

Average End-to-End delay during the network lifetime is presented in Figure 5.13. This metric can measure the overall delay during protocols' lifetime until all nodes die (LND). Therefore, it gives a good view to evaluate the performance of these protocols even they lose some of their nodes and other nodes still have packets to send to the BS. DCBRP routing protocol makes single hop between chain heads and BS, thus it will deliver the network data quickly. CCM applies a single hop among all chain heads and the main head node to avoid the chain delay in the CHs nodes. Therefore, CCM performs better than TSCP routing protocol since it applies two stage chains which affect the receiving time of all packets in the WSN.

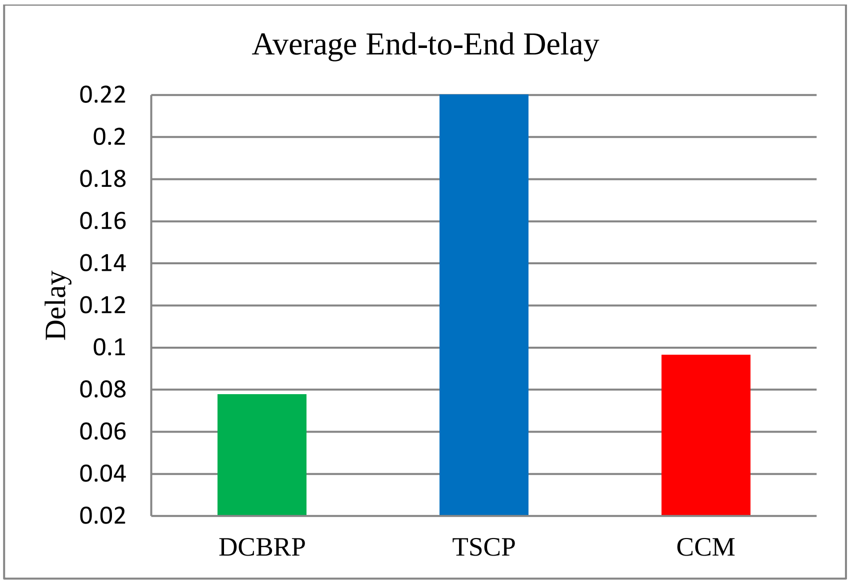


Figure 5.13. Average End-to-End delay for DCBRP, TSCP and CCM (LND)

Finally, DCBRP protocol outperforms the CCM and TSCP protocols in terms of average end-to-end delay until LND, such that the average delay is 0.07788 ms, 0.2230 ms and 0.0966 ms for DCBRP, TSCP and CCM, respectively. DCBRP routing protocol enhances important metric in the chain-based routing approach in WSN with the positive effect of BCM and CHS mechanisms and thus outperforms the TSCP and CCM by 65% and 19.38, respectively.

5.3.4 Energy*Delay

In chain-base routing protocols, Energy*Delay computes the amount of trade-off between delay and energy consumption to achieve the equilibrium between energy efficiency and other performances metrics [156]. Therefore, the WSN researchers use this metric to evaluate the performance of chain-based routing protocols. In other words, it is difficult to avoid delay in the chain-based routing protocols since it has compulsory data redundancy from source to distension and thus has significant improvement in energy consumption. Figure 5.14 shows that DCBRP protocol has significant superiority over the other protocols with respect to Energy*Delay metric.

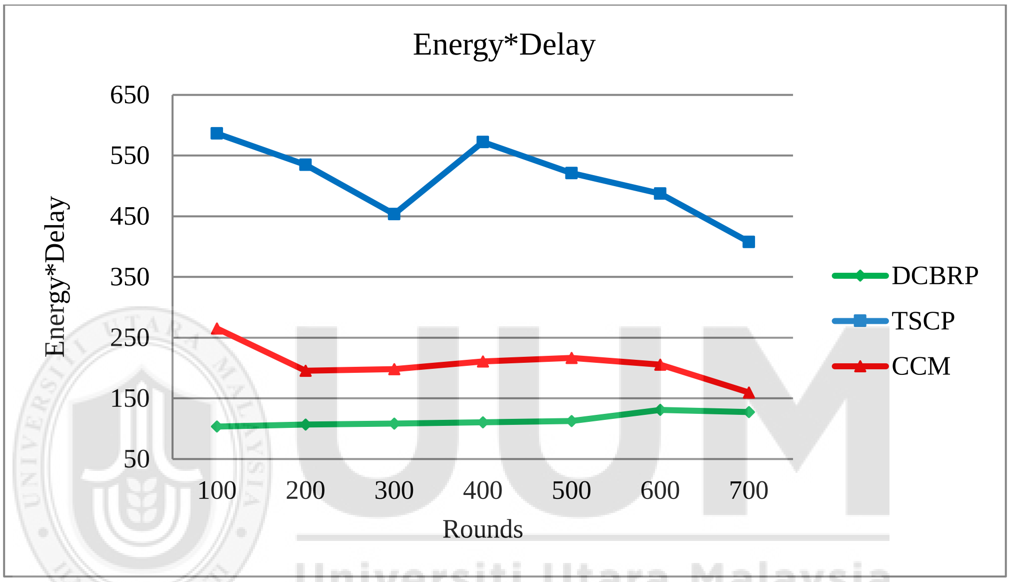


Figure 5.14. Energy*Delay Metric for DCBRP, TSCP and CCM Protocols

DCBRP routing protocol has good performance in the End-to-End delay and energy consumption by applying its mechanisms, which include BCM, CHS, and NHC mechanisms. Consequently, it will double the Energy*Delay when the multiplication operation is applied between two small numbers. DCBRP routing protocol also adds more stability for the network depending on NHC. The weak nodes are eliminated to join the main chain without increasing the number of hops during the packets traveling from source to the BS.

5.4 Summary

Different scenarios were used in this chapter to evaluate the performance of DCBRP routing protocol in comparison with TSCP and CCM protocols. Data fusion was applied in the first scenario in all sensor nodes; each node receives data from its neighbour, then fuses it with its own data and then sends it as one packet. DCBRP shows superiority on TSCP and CCM in terms of four performance metrics, i.e., delay, energy consumption, network lifetime, and energy*delay. Furthermore, TSCP outperforms CCM in terms of energy consumption, network lifetime, and Energy*delay metrics. While CCM still has advantage in delay more than TSCP because of clustering between the CHs. Moreover, in “without data fusion” scenario, the results show that DCBRP outperforms CCM and TSCP in terms of end-to-end delay by 19.3%, 65%, CH energy consumption by 18.25%, 23%, overall energy consumption by 23.7%, 31.4%, network lifetime by 22%, 38%, and energy*delay by 44.85 and 77.54 %, respectively.

CHAPTER SIX
CONCLUSION AND FUTURE WORKS

The goal of this research is to develop chain based routing protocol for deterministic nodes' deployment in WSN. In addition, this research highlights the performance evaluation of the DCBRP routing protocol with other protocols. Therefore, this chapter provides the conclusion and the main contribution of this research. In addition, this chapter also presents the research limitations and suggestions for the future research.

6.1 Research Conclusion

This research motivated by the importance of routing protocols in WSN, as presented in Chapter Two. The sensor energy is limited, therefore, designing a routing protocol is very important and effective protocol can reduce energy consumption and prolong network lifetime [66]. WSN with Direct Transmission protocol will spend a lot of its energy rapidly impacting negatively on all nodes to suffering from the distance with BS. Therefore, there is no way to use efficient routing protocol as well as to manage the nodes connection in WSN. Two important things should be considered when designing routing protocol. These include the delay and energy consumption because they are directly related to network lifetime and quality of data delivery. Thus, DCBRP routing protocol is developed and evaluated in this research with its mechanisms.

DCBRP routing protocol consists of three mechanisms, namely BCM, CHS and NHC. The DCBRP protocol shows the superiority in performance evaluation metrics which include delay, network lifetime, energy consumption, and energy*delay. This behaviour of DCBRP routing protocols comes from the impact of its mechanism. Where BCM mechanism effects delay metric by dividing the network into specific number of clusters depending on the number of columns, and reduces the number of chains in the network while applying the Chain-based approach by each node connected with its neighbour only.

CHS mechanism works to select the strongest node in every cluster to play chain head role according to its ability for data delivery to the BS. This mechanism will select the chain head efficiently depending on the CHS_{factor}. It saves the energy of other nodes and keeps it for sensing purposes. The CH node may change in the next round depending on the nodes' status and parameters. Consequently, the energy consumption for CHS in DCBRP protocols shows less energy consumption comparing with other protocols and thus it provides opportunities for other nodes to prolong the network lifetime for more sensing rounds.

Finally, the results show that DCBRP routing protocol has 2013 rounds before the first node dies, while TSCP and CCM have 1739, 1540 rounds for FND, respectively (data fusion apply). These results come from the impact of NHC mechanism, which is the third mechanism in DCBRP. NHC prevents the weak nodes from the main chain in all clusters to help those nodes which have little energy to maintain their life. The main chain nodes are responsible to deliver the previous nodes' data in the chain as well as their own data to the next hop and so on. Figure 6.1 shows the first round for the packets route using DCBRP routing protocol.

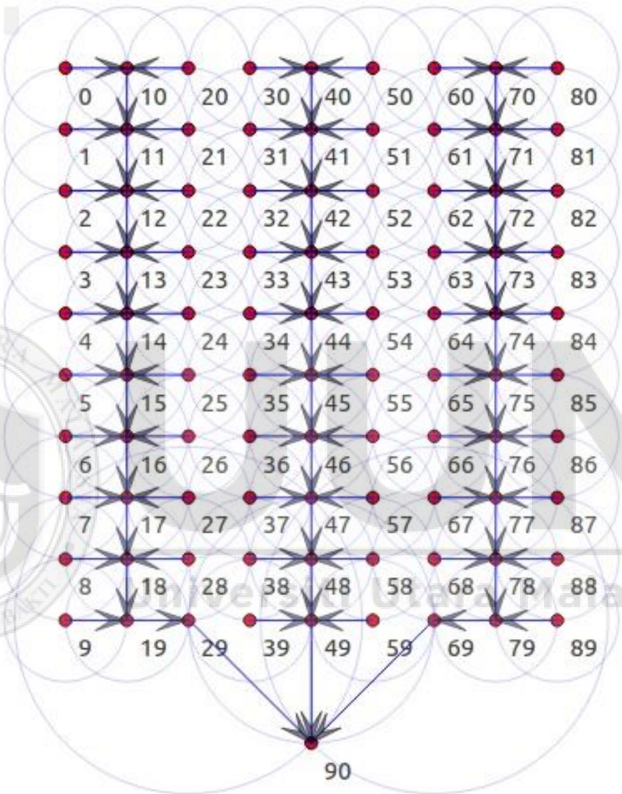


Figure 6.1. Packets Routing by DCBRP Protocol

Moreover, the main purpose of WSN is to monitor the around area or sensing something and transfer this data to the BS. Therefore, the essential objectives of routing protocols are to help the sensor nodes do these tasks as long as possible to ensure the sensing nodes cover all the target area. However, routing area needs important enhancement in each phase of its communication. Thus, the DCBRP routing protocol is proposed and evaluated in this research as a plausible solution to the drawbacks in the chain-based routing approach. These include delay, energy consumption, and the ability to prolong the network lifetime.

In addition, the DCBRP routing protocol considers the main contribution for this research and it consists of three main mechanisms that are:

A- **B**ackbone **C**onstruction **M**echanism (**BCM**): This mechanism is responsible to do the following tasks:

   a. Computing the number of clusters in the network by Equation 4.1

   b. Computing the number of columns in each cluster by Equation 4.2

B- **C**hain **H**ead **S**election mechanism (**CHS**): The main tasks for this mechanism are to complete the following errands:

   a. Assigning the number of chain head nodes, which is one node for each cluster depending on the number of clusters in the network

   b. Selecting a chain head node in each cluster depending on the ability of data delivery to be sent to the cluster nodes and the BS based on the CHS_{factor} from Equation 4.7

C- **N**ext **H**op **C**onnection mechanism (**NHC**): This mechanism is designed to do the following tasks:

  a. Balancing the energy consumption between nodes as much as possible

  b. Selecting the next hop connection in each data transmitting between rows to avoid the weak node from being a member in the main chain by the NHC_{factor} from Equation 4.10

Finally, it is also imperative to note here that whenever DCBRP routing protocol is mentioned, its three important mechanisms should be highlighted as each part complements other parts.

6.2 Limitation and Future Work

The potential of deterministic node deployment in target area is its compatibility with DCBRP routing protocol. Because DCBRP routing protocol is not developed for random nodes deployment applications, this protocol and its mechanisms depend on the fix nodes position. However, this research opens many new research trends for routing protocols in WSN such as:

- Applying BCM, CHS and NHC mechanisms in heterogeneous nodes to prolong the network lifetime should be investigated in the future

- Applying BCM, CHS and NHC mechanisms with mobility base station to make energy balancing according to nodes distance with the BS should be considered in the future

- Applying CHS and NHC mechanisms in random nodes deployment applications that may be very useful for developing efficient protocol for random nodes deployment.

- Evaluating the DCBRP protocol in terms of packet overhead and compute the time complexity computation.

Furthermore, DCBRP can be adapted to other sensor areas, such as Internet of Things (IoT) [157] and be used in cross layer protocols at MAC layer. Therefore, DCBRP offers promising protocol to be the base for any future work in routing protocols research in WSN through its flexibly mechanisms and its Equations.

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