Reliable and Energy Efficient Cluster-Based Routing Protocols for Wireless Sensor Networks

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Anwar Sadat

March 2012

Dedicated to my parents for all their love and inspiration.

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Abstract

Cluster-based routing protocols for wireless sensor networks have proved to be a very popular and effective innovation. They are inherently energy efficient and scalable owing to the distributed nature and hierarchical organization of sensor nodes, as well as the use of cluster heads in data reception, aggregation and transmission. However, their reliability is very limited because of the potential for sudden break down and the traffic congestion in a cluster head. A wireless communication link is also vulnerable to interference and noise. In addition, to form an optimal cluster is a *NP hard* problem. These problems make it very challenging to improve the *reliability* and *energy efficiency* simultaneously. To address these issues, this thesis proposes a number of cluster-based routing protocols that consider many challenging issues, such as the cluster number determination, the inter-cluster communication cost, the link quality and traffic congestion during the node clustering phase.

This thesis contributes four innovative methods that improve both the *reliability* and *energy efficiency* of a wireless sensor network simultaneously. The first of these contributions is *an optimum backup clustering technique*, which reduces the re-clustering overhead of the network and safeguard a cluster head node from sudden break down. The second method, *reliable and energy efficient inter-cluster communication*, reduces the chance of a cluster head breakdown by developing routing paths that consider the optimal inter-cluster communication cost. This method also considers data loss due to poor link quality and congestion at the CH node. The third method, *optimum cluster number determination technique for uniform wireless sensor network*, integrates the wireless link quality factor analytically for estimating the optimal cluster number to be used in any suitable clustering protocol. Finally, *joint optimization of number and allocation of clusters* is introduced, which calculates the optimum cluster number at the time of node clustering. This is applicable in a wireless sensor network with both uniform and non-uniform node distributions.

The performance of all the proposed methods is evaluated along with the com-

putational complexity analysis and message overhead. To check whether the method promotes a sustainable environment, performance analysis of the backup clustering scheme has been presented for a certain portion of sensor nodes equipped with a solar cell. Statistical tests confirm that the new clustering methods exhibit significant improvements in terms of both reliability and energy efficiency over the most popular contemporary clustering protocols (e.g. HEED and only one existing backup clustering technique) with the comparable computational complexity and message overhead.

Acronyms

ACK	Acknowledgement
ADV	Advertisement Message
AODV	Ad-hoc On-Demand Distance Vector routing
BCH	Backup Cluster Head
BS	Base Station
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CH	Cluster Head
CSMA	Carrier Sense Multiple Access
DLR	Data Loss Ratio
DP	Domatic Partition
DS	Dominating Set
DSDV	Destination-Sequenced Distance-Vector routing
DSR	Dynamic Source Routing
GAF	Geographic Adaptive Fidelity
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GUI	Graphical User Interface
MAC	Media Access Control
MANET	Mobile Ad hoc Network
PDA	Personal Digital Assistant
PER	Packet Error Rate
PLR	Packet Loss Ratio
PV	Photo Voltaic
QoS	Quality of Service
RSS	Receiving Signal Strength

TDMA	Time Division Multiple Access
UDG	Unit Disk Graph
WSN	Wireless Sensor Network

Nomenclature

A	Area of sense zone
ARE	Average reachable energy
B_{size}	Buffer size of a node
B_j	Packet loss due to congestion at CH node, CH_j
C_i	Number of members in i^{th} cluster
C_{ij}	Number of multi-hop traffic relayed by CH_i node
d	Transmission distance
D	Set of all edges for the inter-cluster communication
d_0	Characteristic distance
$d_{non-CH,CH}$	Distance between a non-CH member node and its respective CH node
$d_{CH,CH/BS}$	Distance between two CHs or between CH and the BS
$erfc$	Complementary error function
e_{elec}	Energy required for electronic circuitry
E_i	Initial energy of a sensor node
E_{da}	Energy required for data aggregation
E_{sw}	Energy required for cluster head switching
E_c	Energy consumed by a node
E_{RE}	Residual energy of a sensor node
E_{CH}	Energy consumed by a CH node
E_r	Receiving energy
E_t	Transmission energy
E_M	Power at maximum power point
E_{non-CH}	Energy consumed by a non-CH member node
E_{max}	Maximum energy of the sensor node
E_S	Sensing energy of a sensor node

E_s	Transferred solar energy to a sensor node
k	Number of member nodes within a cluster
l	Number of Bits in a message
$L_{i,j}$	Link quality between node i and j
m	Number of re-transmissions
n	Total number of nodes in the network
N_{non}	Number of non-overlapping nodes
p_b	Broadcast packet size
p_e	Bit Error Probability
P_i	Switching parameter
p_p	Packet Error Probability
p_{pkt}	Data packet size
p_{op}	Optimal probability
P_{leak}	Leakage power profile
P_r is the received power	
P_n	Noise power
q	Total number of clusters in the network
R	Transmission Range
T_B	Transmission bit rate
r_c	Cluster Radius
T_C	Clustering time of the whole network
t_{CH}	Time for a node to act as a cluster head
T_R	Network Operation Round
T_N	Network operation time
t_{non-CH}	Time for a node to act as a member node
w	Frequency of re-clustering
W	Channel bandwidth
σ	Node Density
η	Solar cell efficiency
ρ_s	Solar illumination

ε_{fs}	Free space channel fading co-efficient
ε_{mp}	multi-path channel fading co-efficient

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Chapter 1

Introduction

1.1 Wireless Sensor Network Background

Wireless Sensor Networks have been identified as one of the most promising technologies of this century. Researchers have been exploring the potential and efficient usage of WSNs over the last decade mainly because of their ability to operate independently in harsh environments that are inaccessible or hazardous for a human being. A sensor node of WSNs is a tiny electronic device that is capable of detecting physical phenomena, such as temperature, light, heat, sound, and so on. Each sensor can perform the gathering, processing and transmitting of this information to a nearby node wirelessly. This new technology poses many challenges that need to be solved and these provide the goals of this thesis (see Section 1.3).

Thanks to technological advances in recent years, the size of sensors is becoming smaller with increasing capabilities, and they are cheaper in price. These advances have expedited the widespread development of numerous cutting edge WSN applications. Sensor network applications are taking over many crucial monitoring and detecting activities, such as monitoring industrial machinery, machines attached to patients' bodies and changes in environmental phenomena, such as radio-activity, chemical affects and so on. In these applications sensors are deployed in large numbers and are expected to operate independently for a long period of time. As these tiny sensor nodes are embedded with a limited power supply and replacement of these batteries is either impossible or uneconomical, it is very important to ensure the efficient utilization of the energy of a node.

The architecture of the sensor node's hardware consists of five components: (i) sensing hardware; (ii) processor; (iii) memory; (iv) transceiver; and (v) power supply. To cover a vast geographical area, sensor nodes are now deployed in large numbers. In a WSN, the spatially distributed nodes collectively form a network to transport the sensed data towards the remote base station (BS) by wireless communication.

Over the past several years, a significant amount of research has been carried out regarding WSN data gathering protocols. Sensor applications require the long-term and reliable reception of sensed data. However, designing WSN protocols has become challenging, as the operation of sensor nodes is limited by their energy supply and bandwidth. A large number of research initiatives have been undertaken to overcome these limitations. Addressing the requirements of sensor applications in the context of the deployment of a large number of sensor nodes demands the design and development of stat-of-the-art techniques at all layers, including the physical, MAC, network and application layers. The physical layer converts bit streams into signals for communication. More specifically, the physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption. IEEE has developed IEEE 802.15.4 [3] for low-power wireless communication. Each sensor node shares the wireless channel with the nodes in its transmission range. Since the communication takes place in this wireless channel, the design of Medium Access Control (MAC) protocols is crucial. The MAC protocols (e.g., B-MAC [4], [5]) ensure the communication links and connectivity, and minimize collisions at the time of communication between nodes. The role of the application layer is to abstract the physical topology and provide the necessary interfaces to the user. The application layer protocols (e.g., Sensor LZW(S-LZW) [6], SQTL [7], SNMS [8]) usually perform source coding, query processing, and network management. On the other hand, the network layer is one of the most important research areas in WSNs. In this thesis a wide range of routing protocols have been proposed that will be discussed in the next section.

1.2 Routing Protocols for Wireless Sensor Networks

As a WSN system does not have a fixed infrastructure, it poses a different kind of challenge in terms of design constraints than do infrastructure-based wireless networks (e.g. cellular networks and wireless LANs). A WSN shares many of the challenges of the traditional wireless networks such as wireless link quality bandwidth and so on. However, there are additional challenges that are encountered in the development of WSNs. Sensor nodes are often deployed in high density and large numbers, such that it is impossible to build a global addressing scheme for them as the overheads of ID maintenance are too high. Thus, traditional IP-based protocols cannot be applied to WSNs. Additionally, a large number of deployed wireless sensor nodes produce a large amount of sensed data. Transportation of this data encounters time-varying wireless link quality and congestion at the sensor nodes, which introduces data loss in the network. Another property of a WSN is that its topology can change suddenly and unpredictability due to energy exhaustion and failure of the sensor nodes, causing further loss of data. Therefore, ensuring a reliable transfer of data from the source node to the BS is of paramount importance.

Routing in a WSN is nontrivial, as the routing mechanism has to consider the inherent features of WSNs. It is necessary to carefully identify the routing metrics for WSNs through an investigation of existing routing protocols. We classify WSN routing protocols (Fig. 1.1) into two categories based on the underlying network structure. These are: (i) data-centric or flat-based; and (ii) hierarchical or cluster-based routing.

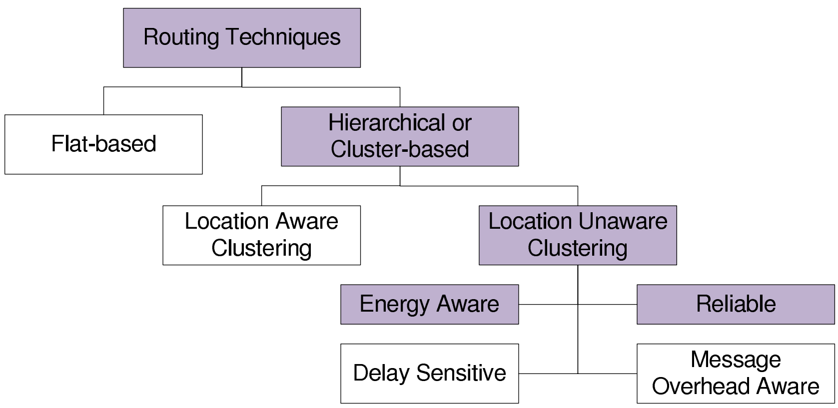

Figure 1.1: Classifications of WSN routing techniques.

1.2.1 Flat-Based Routing

In flat-based routing (e.g., Sensor Protocols for Information via Negotiation (SPIN) [9], Directed Diffusion [10], GBR [11] and so on), each sensor node performs the same set of tasks. Here, nodes produce redundant data and apply flooding (broadcasting data throughout the network) type data transfer. Two major limitations of flat-based routing protocols are: (i) implosion and (ii) overlap. The former is inherently embedded in classic flooding, where a node sends data to its neighbours, regardless of whether or not the neighbour has already received the data from another source. The latter arises automatically, as nodes often cover overlapping geographic area, and gather overlapping pieces of sensor data. Both implosion and overlap of the routing algorithm wastes the nodes' valuable energy and the bandwidth of the system. SPIN efficiently disseminates information amongst sensors and eliminates the transmission of redundant data throughout the network. The communication decision of SPIN depends on the application of specific knowledge of the data and knowledge of the available resources. Due to the problems of excessive energy consumption and inefficient bandwidth utilization, flat-based routing techniques are deemed unsuitable for WSN applications.

On the other hand, in hierarchical or cluster-based routing protocols (e.g., LEACH [12], PEGASIS [13], HEED [14], etc.), instead of all playing the same role, nodes play different roles by forming clusters. In order to exchange messages amongst sensors, which cannot communicate directly, communication take place through the cluster heads (CHs)(Section 1.2.2). The need for scalability and energy efficiency leads to the idea of organizing the sensors into a hierarchy. Hierarchical routing protocols also reduce data traffic and offer better bandwidth utilization. This hierarchical or cluster-based routing technique is described in the next section.

1.2.2 Hierarchical or Cluster-Based Routing

Cluster-based routing has emerged as a popular self-organizing technique for WSNs. Clustering groups sensor nodes into a disjointed and mostly non-overlapping structures in an energy efficient way. Clustering supports many important network features for a WSNs, such as: (i) it reduces packet collisions by better channel utilization; (ii) it improves the network lifetime by reducing energy consumption (iii) it increases the scalability of the network; (iv) it reduces data transportation delay; (v) it reduces the routing table size stored at each sensor node; and (vi) it enhances the stability of the network topology.

In a clustered WSN, member nodes send their data to their respective CH at most once per frame during their allocated transmission slot. The cluster head (CH) node collects data from the member nodes of a cluster, aggregates the data and then transmits the data to the base station (BS) either directly or via other CH nodes (multi-hop communication). Instead of centralizing control at the BS, clustering also decentralizes important tasks; the CH nodes manage their own member nodes; and they take the inter-cluster routing decision based on the routing protocol. Data flow in a clustered WSN is shown in Fig. 1.2.

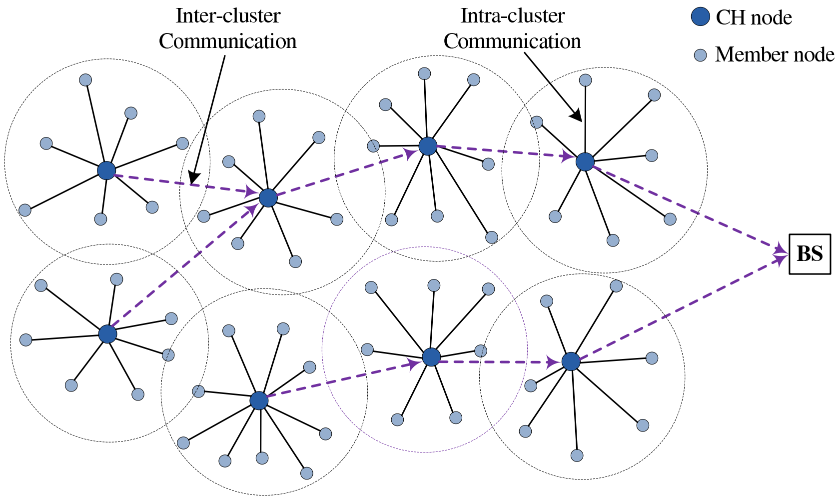

Figure 1.2: Illustration of data flow in a clustered WSN.

WSN clustering techniques have become increasingly popular and as a result the research community has attempted to achieve a number of objectives in relation to them. These are as follows:

- *Maximize network lifetime:* Clustering reduces the number of message transmissions as well as the distance of transmission in the network. Moreover, a CH node can schedule the activities in the cluster so that member nodes can switch to the low-power sleep mode when they are not transmitting. Thus, clustering can effectively reduce the energy consumption of the network.

- *Load balancing:* As CHs are involved in more energy consuming tasks, such as aggregating data, communicating with cluster member nodes and forwarding data to the BS or another CH over long distances, they tend to deplete energy faster than the cluster member nodes. For this reason, to balance the energy consumption amongst all nodes in the network, periodic re-clustering takes place in every clustering protocol.

- *Fault-tolerance:* A CH node coordinates all the activities of a cluster and as a result it can run out of energy, causing sudden breakdown of the node. As a result a part of the network can become disconnected from the rest of the network. Therefore, CH nodes need to be chosen carefully, so that healthy nodes only get the chance to act as CH nodes. To handle a sudden node failure situation, the role of the CH should be efficiently handed over to another backup node for continued operation of the cluster.

- *Increase connectivity:* Ensuring connectivity amongst sensor nodes is an important requirement for many applications. Intra-cluster communication usually takes place over short distances, whereas inter-cluster communication often occurs at large distances, where connectivity between CH nodes is a major concern. If a cluster radius increases, it also increases the CH-to-CH communication distance beyond the transmission range of a CH. This situation imposes a boundary on the length of inter-cluster communication in the clustering algorithm. Thus, the connectivity objective in network clustering is a crucial one.

- *Reduce delay:* When data latency is a concern for an application, intra-cluster connectivity becomes a design objective. Delay is usually factored in by setting a maximum number of hops allowed on a data path. Therefore, the clustering algorithm need to select clusters optimally to reduce delay by considering the hop count.

Clustering of nodes in wireless networks is a well researched field [15]. Most published approaches to clustering base the selection of a CH on different factors, such as cluster ID, degree of connectivity [16, 17] or randomization [12]. A frequent selection of CHs is desired if the topology is constantly changing or if the load has to be shared amongst all the nodes. If traditional clustering approaches, such as highest connectivity or node ID, are applied, the same node will be picked as CH every time, resulting in the sensor draining its energy very fast. The clustering approaches developed for the wired network cannot be applied directly in WSNs due to the unique characteristics and deployment pattern of these networks. Many of the WSN clustering techniques that have been proposed in the literature mainly tried to prolong network lifetime, without much concern for the critical design goals of WSNs, such as network reliability and messaging overhead. Each of these existing cluster-based routing protocols have achieved particular goals based on a certain performance metrics.

There are several ways of classifying all clustering protocols. As shown in Fig. 1.1, the hierarchical or cluster-based routing protocols can be either location aware or location unaware.

Location aware: Location aware routing techniques exploit the location information of nodes. There are several location aware cluster-based routing protocols ([18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28]) available in the literature. There are many ways that location of nodes can be calculated, such as centralized, range-based or absolute localization. In centralized localization, the BS requires network-wide node information for computation. After computation, the BS again sends the location information back to each node (e.g. [29]). This method introduces excessive energy consumption, longer delays and larger network communication traffic. A range-based localization method utilizes the distance and angle between nodes to obtain the location of an unknown node. For location calculation, nodes typically use trilateration, triangulation and maximum likelihood estimation (e.g. [30]). Range-based localization methods need extra hardware and energy consumption in the network. On the other hand, absolute localization is GPS-based localization. However, GPS embedded sensor nodes can sometimes be misleading when their line of sight is blocked [31] (e.g. inside a room, a parking lot, or a tunnel, etc.). Moreover, it is expensive to attach a GPS unit to a cheap sensor node.

Localization techniques provide a range of location information, rather than precise information. As a result, nodes within a short distance of each other may provide the same result. Due to these shortcomings, it is not worth developing a clustering technique for a WSN with location aware nodes. Even with a known location information of the node, efficient selection of a CH may not be possible. This occurs because two nodes may seem close to each other geographically, and yet radio connectivity between them may be weak or absent due to an obstacle or other reasons. Therefore, cluster-based routing or backup clustering based on a location aware node is not practical.

Location unaware: As node clustering in a WSN is essentially carried out based on the application's requirements, location unaware-based techniques can be further classified (Fig. 1.1) based on their quality of service (QoS) performance metrics, such as: reliability, energy awareness, delay sensitivity, and message overhead awareness. Many of the cluster-based routing protocols [12, 32, 14, 33, 34, 35, 36] focus only on energy consumption in the network. Other performance metrics, such as reliability [37, 38, 39, 40, 41, 42, 43], delay [44, 45, 46, 47], and message efficiency [48, 49] have also been considered in cluster-based routing protocol design.

Ensuring reliability is a major concern into the research of WSN data transportation, especially for location unaware WSNs. Some critical WSN applications (e.g., monitoring patients' health, military surveillance and intrusion detection, tracking chemical or other toxic material leakage in industry, detection of possible radiological or biological threat to the human body, and so on) require high or even total end-to-end reliability. This necessitates the use of a reliable transport layer protocol. Providing reliability for the wireless network is different from a wired network. In a wireless networks, routing protocols require a minimum level of reliability in order to achieve acceptable degrees of efficiency. Due to the low deployment cost, most applications use a WSN with location unaware sensor nodes. Therefore, hop-by-hop reliability at the transport layer for a location unaware clustering protocol is necessary and becoming a major research issue, while maximizing the energy efficiency.

1.3 Motivation and Research Objectives

While cluster-based routing protocols for a WSN with location unaware sensor nodes can inherently handle a signal fading effect as a result of the presence of an obstacle, and can thus afford inexpensive sensor nodes, clustered WSNs become unreliable mainly due to sudden breakdown of a CH due to excessive usage. As far as we are aware, there are no multi-hop clustering techniques with location unaware sensor nodes that can incorporate the inter-cluster communication cost in the foundation of the clustering process. However, inter-cluster communication takes a major portion of the sensor nodes' energy in WSNs. Additionally techniques for determining the number of CHs and their organization in the hierarchical structure have been developed separately. The estimation process for the number of CHs does not consider the deployment context. This leaves us space for the development of a clustering technique that can determine the CH number and their allocation during deployment, and hence optimize reliability and energy efficiency simultaneously. To address the above mentioned issues, this dissertation aims to achieve the following objectives:

1. Increasing the reliability of cluster-based routing protocols for a WSN with location unaware sensor nodes without sacrificing energy efficiency.

2. The introduction of a framework for incorporating inter-cluster communication cost in the bedrock of a clustering process.

3. The development of an optimum hierarchical structure for a cluster-based routing protocol for WSNs so that reliability and network lifetime are increased simultaneously.

To address the above mentioned objectives, a framework for cluster-based routing protocols (Fig. 1.3) was formulated and developed. The framework includes an unclustered WSN. Four innovative algorithms, identified by Blocks 2, 3, 4 and 5 in Fig. 1.3, are also incorporated in the framework. The concept of introducing link quality and data congestion metrics into the algorithm has made this research suitable for real world sensor applications.

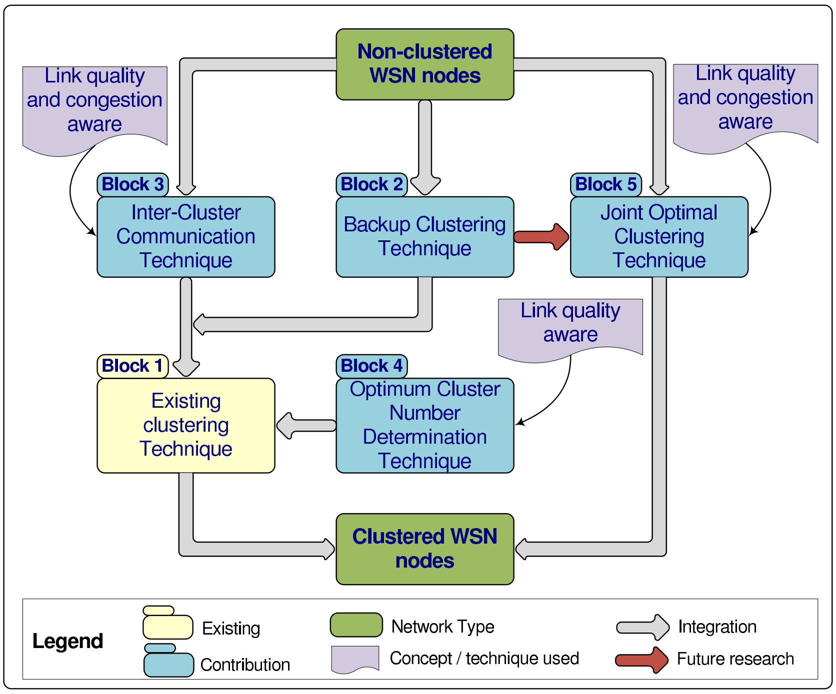

Figure 1.3: A schematic diagram illustrating the major objectives of this dissertation.

In this respect, Fig. 1.3 shows a schematic diagram of the flow of the research conducted to address the objectives presented in the previous section and the mapping between objectives and blocks is shown in Table 1.1.

Table 1.1: Mapping between objectives and blocks.

Objective	**Blocks shown in Fig. 1.3**
1	2
2	3
3	4 *and* 5

According to Fig. 1.3, Block 1 represents an existing suitable clustering technique, where member nodes directly communicate to their respective CH. Objective 1 of this study is shown as Block 2, which addresses the backup clustering scheme and works on top of Block 1. The inter-cluster communication path selection based on cost function is Objective 2 of this project, which is also applicable to any clustering schemes and represented here by Block 3. Objective 3 is highlighted in Block 4, which includes the optimal cluster number determination technique for uniform node distribution. Block 5 also represents Objective 3, which is a jointly optimized clustering technique to achieve both reliability and energy efficiency and that considers intra and inter-cluster communication, link quality and congestion.

1.4 Thesis Contribution

To fulfill the major research objectives, this dissertation presents a number of original contributions. These are as follows:

1. The CH node performs a key role in a clustered WSN. To prevent a CH node from exhausting its energy and sudden death, an efficient backup clustering technique has been devised. This study highlights the limitations of the existing backup clustering techniques and identifies that they are not really energy efficient and that they utilize a a threshold value to switch the CH role. To overcome these limitations, following detailed analysis, an effective backup clustering solution has been introduced, which can be added on top of a suitable WSN clustering scheme. The initial idea for this backup clustering technique was published by Sadat *et al.* in [50] and received *Best Paper Award* in the *ICOIN, 2010* conference (Block 2 in Fig. 1.3).

2. A degraded wireless link quality and excessive traffic congestion at the CH node contributes to major data losses in the network; therefore these factors were investigated in detail in developing an efficient inter-cluster communication technique. Existing inter-cluster communication techniques increase the *hot-spot* problem due to inefficient routing path selection. Therefore, to handle the *hot-spot* problem, a real time update of both the link quality and CH congestion metrics has been considered in this contribution. Here, all types of energy consumption involved in the data transmission and re-transmission process have been explored in order to propose two schemes that offer: (i) a trade-off between reliability and energy efficiency; and (ii) an optimum route selection scheme. Both of these research works are published by Sadat *et al.* in [51] and [52] (Block 3 in Fig. 1.3).

3. Clustering algorithms need to know the number of clusters for the network. However, wireless communication is always vulnerable to signal interference, environmental noise and so on, which can cause data loss. This data loss has a huge impact on the calculation of an optimal cluster number. Therefore, this study introduces a technique to determine the optimal number of clusters for the network with uniform node distribution and incorporating link quality. This research project is published by Sadat *et al.* in [53] (Block 4 in Fig. 1.3).

4. Finally, a novel Joint Optimal Clustering (JOC) technique has been developed for jointly optimizing the number of clusters and the clustering process so that both reliability and energy efficiency are maximized. This technique is applicable for WSNs with both uniform and non-uniform node distributions. Both intra and inter-cluster communications are taken into consideration during the joint optimization process. Important aspects, such as the wireless link quality and congestion at the CH node were considered for better suitability of the protocol to a real life context. The proposed JOC technique gives a unique platform for a WSN to achieve both reliability and energy efficiency. The initial idea for the JOC technique has been submitted to the *ICC 2012 conference* [54] (Block 5 in Fig. 1.3).

An evaluation of the performance of all the algorithms introduced in this thesis, is carried out using a widely used simulation testing tool called, TOSSIM, which is a discrete event simulator for TinyOS (A popular operating system nowadays). Moreover, the TOSSIM code can execute on a real sensor node platform. We used the HEED [14] and BCH_Hashmi [55] protocols to compare the performance of our algorithms with. The network lifetime, data loss ratio, and message overhead have been used as performance metrics at the time of the evaluation of the algorithms. For network lifetime estimation, we considered both the time until the first node and last node death of the network. The suitability of the proposed backup clustering technique whether the algorithm promotes a sustainable environment, is carried out with a certain portion of sensor nodes equipped with a solar cell.

1.5 Organization of the Thesis

The thesis is organized as follows:

Chapter 2 presents existing WSN clustering algorithms available in the literature. This dissertation aims to propose a reliable and energy efficient clustering scheme for a WSN. Clustering a WSN, where sensor nodes are location unaware, is a challenging issue. To efficiently cluster a network, it is first necessary to study the existing clustering techniques. We categorized all current clustering techniques and pointed out the advantages and disadvantages of each of them.

Chapter 3 presents a reliable and energy efficient backup clustering technique. The backup clustering technique improves the reliability of the network by reducing frequent re-clustering and the CH node failure of a clustered WSN. This technique, which considers the remaining energy of a sensor node, switching energy and average reachable energy, aims to optimally select a set of Backup Cluster Heads (BCHs). The technique also eliminates the requirement of manually selecting the threshold to switch to a BCH. A performance evaluation using a simulation of the developed backup clustering technique with and without using solar harvesting nodes is also presented in this chapter.

Chapter 4 introduces a reliable and energy efficient inter-cluster communication technique that considers both link quality and traffic congestion at the CH node. Two routing path selection techniques: (i) a trade-off between reliability and energy efficiency; and (ii) optimal scheme, along with their performance evaluations, are presented in this chapter.

Chapter 5 proposes a novel technique for joint optimization of the number and allocation of clusters for a WSN. This algorithm achieves significant improvement in terms of reliability and energy efficiency and is suitable for both uniform and non-uniform node distribution. Along with the performance analysis through simulation, this chapter also presents a theoretical model for optimization and defines an algorithm to solve the model numerically.

Finally, Chapter 6 presents the conclusions derived from the research and explores some new research directions based on the original findings presented in the thesis.

Chapter 2

Review of Clustering Protocols for Wireless Sensor Networks

The significance of and research motivation for the cluster-based routing protocol for a WSN has been articulated in Chapter 1. This promotes us to advances the concept of clustering technique to improve both the reliability and lifetime of a WSN. Before presenting the contributions of this research project in subsequent chapters, it is necessary to carry out an extensive study of the existing literatures. Therefore we have performed a detailed investigation of the clustering techniques available in the literature. These include the cluster formation, the cluster number determination and proxy or backup cluster head selection and switching techniques. Relevant research in this domain, based on the issues highlighted in Section 1.4, are critically analysed in this chapter. In this regard, we present the state-of-the-art WSN clustering techniques that have been devised to achieve different performance gains, along with their limitations (Section 2.1). This section also the explores existing proxy or backup clustering techniques to attain fault-tolerance and further energy gain for WSNs. Following this, we elaborate on the different methods for determining the optimum cluster number for a WSN (Section 2.2). Finally, we conclude by summarizing the chapter (Section 2.3).

2.1 Wireless Sensor Network Clustering Techniques

A large number of clustering techniques have been appeared in the literature over the last couple of decades. These techniques aim to achieve a number of key parameters, such as maximizing network lifetime, reducing delay, enhancing reliability, achieving fault tolerance, maintaining coverage and connectivity, and so on. Each of the existing protocols mainly deals with one of the above aspects and tries to obtain a particular performance gain. Although all researchers have discussed their specific problems and challenges, increasing the energy efficiency of the network seems to be the major goal for the majority.

Several survey papers [56, 49, 57, 58, 59, 60, 61] and tutorials have categorized some of these protocols based on certain parameters or their design approaches. The available literature on cluster-based routing protocols for WSNs can be broadly classified based on different criteria, such as the performance metrics used, or whether they are location unaware or aware, and so on. Although a location aware sensor node can provide extra flexibility in the design of the clustering algorithm, a node with GPS [62] facilities, or development of a method to determine the position of a node, is costly. As sensor nodes are very cheap and tiny, most of the protocols developed are for location unaware sensor nodes. For simplicity in presentation, all the clustering techniques are broadly classified as either (i) location aware, or (ii) location unaware clustering techniques. These are elaborated in the following section.

2.1.1 Location Aware Clustering Techniques

As mentioned previously, although location aware sensor node in a WSN can provide extra flexibility in the design of the clustering algorithm, using a node with GPS facilities or a method to determine node location is costly. This cost may hold back the wide-spread deployment of a WSN. In this section, we discuss the location aware clustering techniques that have been developed to achieve some performance metrics, such as energy efficiency, reliability, fault tolerance and so on. Based on these, we can broadly classify all the location aware clustering techniques into the following two classes: (i) traditional clustering, and (ii) proxy-enabled clustering techniques. These are described in the following sections.

2.1.1.1 Traditional Clustering Techniques

A number of energy efficient clustering algorithms have been proposed [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28] where the sensor nodes are location aware. In [18], the authors pointed out that clustering techniques usually fall into two families: (i) those based on the construction of a dominating set and (ii) those that are based solely on energy considerations. In relation to the former family, only a small subset of nodes become responsible for relaying the messages. Therefore, these nodes suffer from a rapid consumption of energy. The latter family uses a method of selecting a CH based on the remaining energy of the nodes and hence ignores the topological features of a node. To overcome these problems, this research presented a distributed clustering protocol named GESC [18], which uses a novel metric for characterizing the importance of a node with respect to its contribution in relaying messages. In the authors' cluster formation procedure, they assumed that nodes in a WSN periodically exchange "Hello" messages with their neighbours, which contain the list of their 1-hop neighbours. Thus, each node is able to form a graph that corresponds to its 2-hop neighbourhood (or its 1-hop neighbourhood). Furthermore, when a packet is received, each node is able to identify from which 1-hop neighbour this packet was sent. The protocol elects CHs depending on the location of the source and the progress of the clustering process. The proposed protocol achieves a small communication and linear computation complexity. It also generates few clusters, guaranteeing a small relay message overhead and improving the network lifetime. However, due to the generation of few clusters in the network, the proposed approach causes an energy burden for the CH nodes.

A Distributed Weight-based Energy Efficient Hierarchical Clustering (DWEHC) protocol is developed by Ding *et al.* [19] to achieve more aggressive goals than those of HEED [14] (detailed in Section 2.1.2.1). This protocol selects a CH based on the largest weight, where weight is a function of a node's residual energy and the distance to its neighbours. DWEHC constructs multilevel clusters, where the level depends on the cluster range. At this stage the nodes are considered as first-level members, as they have a direct link to the CH. A node progressively adjusts its membership in order to reach a CH using the least amount of energy. A node checks with its neighbouring member nodes in order to find out their minimal cost for reaching a CH. Using the knowledge of the distance to its neighbours, it can assess whether it is better to stay a first level member or become a second-level one, reaching the CH over a 2-hop path. The process continues until nodes find out the most energy efficient intra-cluster topology. To limit the number of levels, every cluster is assigned a cluster range to maintain a certain intra-cluster topology as illustrated in Fig. 2.1. DWEHC generates more well-balanced clusters than HEED and also achieves significantly lower energy consumption in intra-cluster and inter-cluster communication. Although they proposed Time Division Multiple Access (TDMA) [63] within the cluster in order to

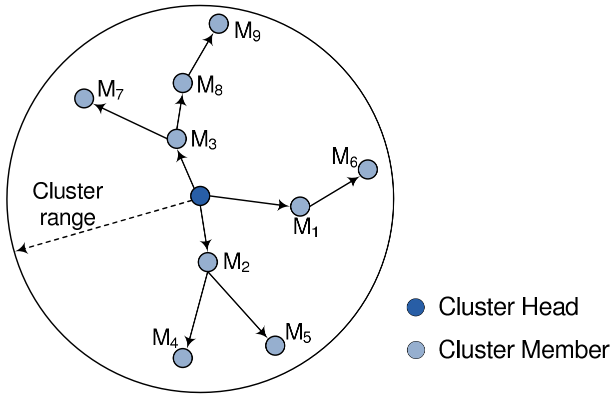

Figure 2.1: A intra-cluster topology generated by DWEHC with the CH at the root.

avoid the collision, Ding *et al.* have not discussed how the TDMA will be used when nodes in each cluster reach the CH by relaying through other nodes.

Dynamic clustering techniques suffer from an energy overhead. Periodic selection of CH nodes in the cluster setup phase of the LEACH [12] protocol (detailed in Section 2.1.2.1) has been identified as an excessive energy consuming process and, thereby, the Energy-Efficient Protocol with Static Clustering (EEPSC) [20] was introduced. EEPSC uses static partitioning of the network in order to eliminate the overhead of dynamic clustering. Here, cluster formation is performed only once at the beginning of the network operation. The BS randomly selects one temporary CH for each cluster and also sets up a TDMA schedule and transmits this schedule to the nodes in each cluster. Afterwards, every node sends its energy information to the temporary CH. Based on energy information, the temporary CH chooses the node with the highest energy to act as CH for current round. This collects the data of sensor nodes of that cluster, performs local data aggregation, and communicates with the BS. In addition, the node with the lowest energy level is selected as temporary CH for the next round. The temporary CH also sends a round-start packet, including the new responsible sensor IDs for the current round. This packet also indicates the beginning of round to other sensor nodes. As every node has a pre-specified time slot, changing the CHs does not have any effect on the schedule of the cluster operation. Although this process selects a CH node with the highest energy, it cannot guarantee minimum energy consumption in the network, as the position of CH node may not be at the center of the cluster. Furthermore, due to the involvement of the BS in the clustering process, the messaging overhead is high.

The effective organization of sensors into clusters is a challenging problem. To address this issue, Xin *et al.* [21] presented the Energy-Efficient Clustering Technique (EECT), where they divide the sensed zone into several virtual hexagons to avoid the overlapping of the nodes in a circular cluster during the clustering phase. In this protocol the BS collects the average distance between nodes and the virtual hexagon's center and computes the cluster radius. Then, based on the area and the node density, the distance between any two nodes is calculated. The BS continues computation until the average distance is less then the distance between any two nodes. This technique, however, employs a huge message overhead to find the optimal cluster radius and limits the network lifetime as the CH transmits data directly to the BS by single hop inter-cluster communication.

Lung *et al.* [22] pinpointed the fact that many algorithms [12, 32, 14] (detailed in Section 2.1.2.1) actually randomly select CHs and force re-clustering under certain conditions. Inefficient or random selection of CHs usually results in low cluster quality. On the other hand, some clustering algorithms focus on building optimized clusters to avoid low cluster quality; however this requires a global network knowledge. Motivated by this fact, the authors presented an efficient clustering protocol, without requiring global network knowledge, by reversing the clustering approach from top-down to bottom-up. In this bottom-up approach, the nodes collaborate and build clusters by grouping similar nodes before they select CHs. To achieve this, Lung *et al.* adapted the Hierarchical Agglomerative Clustering algorithm and developed a distributed energy efficient clustering algorithm called DHAC to enhance the network lifetime. In DHAC, the degree of similarity or dissimilarity between two nodes is identified by a resemblance coefficient, which can be quantitative (e.g. location, Receiving Signal Strength (RSS)) or qualitative (e.g. connectivity). The method uses two predefined threshold values; one is transmission radius, or the number of clusters to split the cluster, and another one is cluster size, based on which a cluster merges with its closest neighbouring cluster and updates its resemblance matrix. After clustering is completed, the selection of CHs begins, where nodes that are in the bottom level, have the lower ID, or the shorter distance to the sink become CH nodes. DHAC also rotates the role of the CH within clusters and forces rescheduling when a CH has low residual energy or when a cluster changes.

Due to the intuitive determination of cluster size by DHAC, the size of the cluster area may be too large and, therefore, consume more energy for the CH. This causes inefficient energy dissipation in the network. To deal with this problem Huang *et al.* [23] extended LEACH [12] (detailed in Section 2.1.2.1) and proposed the Low Energy Fixed Clustering (LEFC) scheme so that the energy efficiency of the network is improved. The protocol assumes that nodes are equipped with GPS and uniformly distributed and considers that the sensing area is divided into a set of square areas. The length of this square is determined so that the energy consumption of the network becomes minimal.

Choi *et al.* [64] identified the problem that data reception and transmission consumes a lot of energy and thus tried to minimize this consumption as much as possible. They addressed the previous work [65, 14] which was aimed at generating the minimum number of clusters but that did not address minimizing the energy consumed in a sensor node. Therefore, it was necessary to minimize the energy used to transmit information from all nodes to the CH. They proposed an energy efficient location-based clustering scheme for a Skewed-Topology [64]. The proposed algorithm increases the network lifetime by reducing the energy consumption of the senor nodes. Here, the clustering scheme separates the sensing area into a certain number of grids, where grid size and node density are imposed by the average number of nodes. Nodes send position information to the BS and the BS executes the algorithm in a fully centralized fashion. Therefore, the algorithm suffers from a huge messaging overhead.

Priyankara *et al.* [24] identified that most of the existing routing protocols do not address the issue of non-uniform energy consumption caused by many-to-one traffic. Therefore they investigated clustering WSNs with heterogeneous node types, where two or more different types of nodes with different battery energy, communication ranges and processing capabilities are used. Priyankara *et al.* [24] proposed that few CH nodes embedded with more complex hardware and extra battery energy can be deployed to minimize the hardware and communication cost for the rest of the network. They introduced a chessboard type clustering that assumes that nodes are location aware, as shown in Fig. 2.2. At the initial stage, high-end sensors determine whether they are in a white or grey cell of the chess board. Then only the sensors in white cells remain active, while the sensors in grey cells turn themselves off. At the same time clusters are formed in the white cells, and high-end sensors become CHs. Later, when the high-end sensors in white cells run out of energy, the high-end sensors in the grey cells wake up and form a different set of clusters in the network. The proposed routing protocol is only applicable for heterogeneous sensor networks consisting of a few powerful high-end sensors. Due to the energy exhaustion of high-end nodes, network connectivity can be greatly decreased. Inter-cluster communication distance increases due to the chessboard type active node selection strategy, which causes more energy consumption in the network.

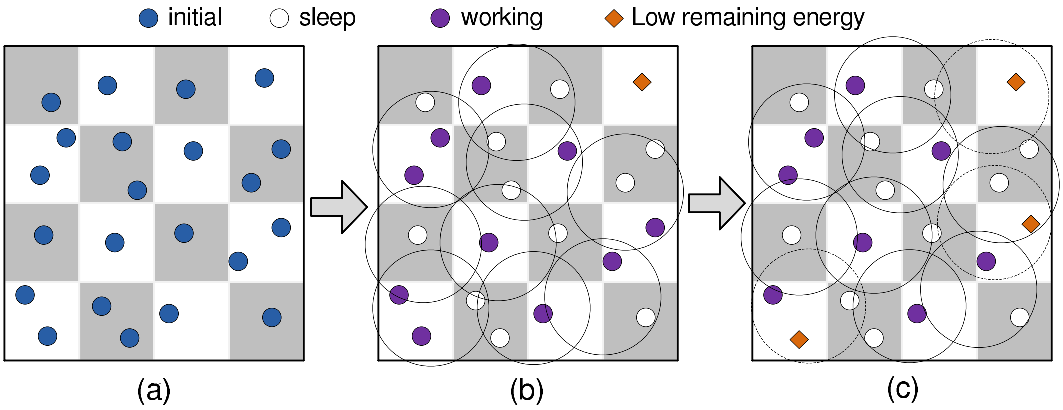

Figure 2.2: Chessboard Clustering: (a) initial state (b) emergence of low remaining energy node, and (c) increase of low remaining energy nodes.

The focus of the existing clustering techniques is mostly to partition the network into clusters [66, 67, 16, 68] without taking into consideration the efficient functioning of all the system components. To address this, Chatterjee *et al.* [25] proposed a Weight based distributed Clustering Algorithm (WCA), which considers the maximum number of nodes a CH can ideally handle transmission power, mobility, and the battery power of the nodes. The proposed WCA protocol adapts itself to the ever-changing topology of ad hoc networks. This scheme considers the mobility of nodes, which disorganizes cluster configuration due to changes in network topology, and therefore reconfiguration becomes necessary. Instead of periodic clustering, which results in a high communication overhead, this protocol is based on the mobility of the nodes. To reduce the computation cost, the clustering process is delayed as long as possible. The protocol uses the weighted combination of node parameters, such as the ideal degree, mobility, transmission power, and battery power of mobile nodes, for electing the CHs.

The calculation of the combined weight W_v for each node $v4$ is as follows,

$$W_v = w_1 P_v + w_2 Q_v + w_3 R_v + w_4 S_v \tag{2.1}$$

where, w_1, w_2, w_3 and w_4 are the weighing factors for the corresponding system parameters. The first component, P_v, of (2.1) helps a CH node to get a certain number of member nodes in its cluster for increasing the MAC functioning. The second component, Q_v is related to energy consumption, assuming more power is required to communicate over a larger distance. The third component, R_v, is due to the mobility of the nodes, where a node with less mobility gets a better chance to be a CH. The last component S_v, is the measure of the total time a node acts as a CH. The node with the smallest W_v becomes the CH node. The CHs form a dominant set in the network. The time required for determining the CHs in the network depends on the diameter of the underlying graph. The protocol also restricts the number of member nodes in a cluster so that it does not degrade the MAC functioning. This algorithm is executed only when a node is unable to attach itself with the existing CHs. The WCA algorithm suffers from a high energy overhead in configuration and reconfiguration of the cluster, and needs further attention to enhance the network lifetime.

Ammari *et al.* [26] identified that it is impossible to guarantee uniform energy depletion of all the sensors of a uniformly distributed node in a WSN. This is because the sensors located around a static sink are used heavily in forwarding sensed data to it. Therefore, they observed the energy sink-hole problem in static sink WSNs, and most real world sensor applications commonly use static sink. According to Ammari *et al.*, the lifetime of a WSN depends on three key design metrics: (i) the type of data forwarding (long range versus short range); (ii) the type of sensors (homogeneous versus heterogeneous); and (iii) the type of sink (static versus mobile) [69, 70, 71]. Therefore, they first considered the transmission distance; secondly, the sensor heterogeneity when deploying sensors; and thirdly, the sink mobility for its ability to evenly distribute the data dissemination load amongst all sensors. The energy of the nodes located near the sink are affected by a significant depletion of their battery power. Ammari *et al.* proved that by adjusting the nodes' communication ranges, this energy problem could be solved. To achieve the goal of uniform energy consumption, they also proposed a sensor deployment strategy based on energy heterogeneity. They propose a localized Energy-aware-Voronoi-diagram-based data forwarding (EVEN) protocol that incorporates sink mobility. The protocol extends the network lifetime significantly compared to a similar data forwarding protocol. It slices a WSN into concentric circular bands of constant width that are equal to the radius of the nominal communication range of sensors where the nodes are location aware. The authors claim that all nodes do not have the same lifetime, as uniform energy depletion cannot be guaranteed under an assumption of constant data reporting by the nodes.

Another energy efficient protocol, called Variable Transmission Range Protocol (VTRP) [27], tried to solving the energy sink-hole problem by varying the sensors transmission range in order to bypass sensors lying close to the sink and avoid their overuse. This protocol addressed three important properties: obstacle avoidance, fault tolerance and network longevity. According to the protocol, obstacle avoidance might be achieved by increasing the transmission range. Increasing the transmission range may also help reach active sensors when the current range does not succeed, either because of faulty or sleeping sensors close to the sensor. Network longevity could be obtained by varying the transmission range to bypass the sensors lying close to the sink and that tend to be overused in the case of fixed range transmissions. It is claimed that this protocol shows high fault tolerance and increases network lifetime as it helps bypass obstacles or faulty sensors. However, bypassing obstacles or faulty sensors often needs a packet to traverse a longer route, which eventually leads to increased energy consumption.

Although these clustering techniques enable the efficient utilization of precious energy, the problem of unbalanced energy consumption still exists. Often the network is organized into equal sized clusters for balanced energy consumption, but such clustering results in an unequal load on the CH nodes. Therefore, an Unequal Clustering Size (UCS) model is proposed in [28] to achieve more uniform energy usage by the CH nodes, and thereby increase the network lifetime. A two-layered network model, as described, has different cluster sizes. According to the theoretical analysis, clusters in Layer 1 should contain fewer nodes than the cluster in Layer 2. The ratio of number of nodes for a cluster in Layer 1 and clusters in Layer 2 varies with each layer and with the aggregation coefficient. This analysis confirms the fact that CHs located near the BS are always burdened with relay traffic from the rest of the network and therefore should have fewer cluster members. The proposed UCS model achieves about 10-30%

improvement over the Equal Clustering Size (ECS) scheme and can lead to more uniform energy dissipation among the CH nodes and increase the network lifetime. This model provides extra benefits for networks that collect large amounts of data from the network. Moreover, this approach can yield a longer lifetime in a homogeneous network, as well as in heterogeneous networks with static clusters.

Generally, clustering algorithms are tightly coupled with an underlying inter-cluster communication mechanism. As a result, cluster formation is largely influenced by the construction of an inter-cluster routing tree. Inter-cluster communication in a clustered WSN can be single hop, multi-hop, negotiation-based, query-based, QoS-based, and so on. Traditional routing protocols have been developed to achieve reduced packet loss, routing message overhead, and route length. As sensor nodes use limited battery power, a comparison and optimization of protocol energy consumption is also important. To address this issue, the Geographic Adaptive Fidelity (GAF) algorithm is proposed in [72], which conserves energy consumption in WSNs by identifying nodes that are equivalent from a routing perspective and then turning off the unnecessary nodes. Each GAF node uses location information to associate itself with a virtual grid, where all nodes in a particular grid are equivalent with respect to forwarding packets. Nodes in the same grid then coordinate with each other to determine which ones will sleep and for how long. This determination is moderated by application and system information. Nodes then periodically wake up and trade places to accomplish load balancing. Analysis and simulation showed that GAF consumes 40 to 60% less energy than an unmodified ad hoc routing protocol. Simulation results also exhibit that the network lifetime increases proportionally to node density.

Many of the proposed clustering algorithms (e.g., [49] and [14]) create more uniform clusters at the expense of overhead in cluster formation. Nodes in WSNs operate on battery power with limited energy and therefore the employed clustering technique must have a low message overhead [58]. To overcome the message overhead, a fully distributed clustering scheme called the Slotted Waiting period Energy-Efficient Time driven clustering (SWEET) [73] algorithm is proposed. If a network starts with equal energy on each node, it gradually evolves into heterogeneous energy, due to non-linear energy dissipation through wireless communication. SWEET prioritizes energy-rich nodes in the CH competition by knowing the energy distribution in advance. A CH candidate running SWEET waits and listens to other neighbours until it becomes a CH, which minimizes the overheads during the clustering process. In SWEET, a CH uses its local transmission range to recruit its member nodes and drives undermining CH contenders away from its cluster radius to restrict the size of the cluster and reduce the competition for CHs. The algorithm multiplicatively increases CH selection probability and employs a back-off strategy during CH selection and placement. SWEET is based on a number of assumptions as to the distribution of initial battery capacities, deployment area size, total number of nodes, desirable number of CHs, and desirable cluster radius. Due to these assumptions this clustering approach is not suitable in many practical applications. Although, the protocol claimed reduced energy consumption due to reduced messaging during the clustering process, the energy consumption takes place in listening to messages and processing messages to find potential contenders during the CH competition.

2.1.1.2 Proxy-enabled clustering techniques

To deal with the node failure situation, which arises due to excessive use of a nodes and to apply balance energy consumption amongst nodes throughout the network, the proxy or backup clustering techniques have been investigated. Several research works have proposed the concept of the proxy node, which can perform the role of a CH if needed and provide extra reliability and fault tolerance in the system. Backup or proxy-enabled clustering schemes have appeared in several research articles, where the primary objective is to enhance the network lifetime and fault-tolerance of a WSN with location aware nodes. The Proxy-Enabled Adaptive Clustering Hierarchy (PEACH) [74] selects a proxy node that can assume the role of the current CH during one round of communication. PEACH uses healthy nodes for the detection and management of any CH failure. Although the protocol claims an improvement in network lifetime over LEACH, it could not extend the lifetime until the first node fails. The Energy Driven Adaptive Clustering Hierarchy (EDACH) [75] proposes a new approach that evenly distributes the energy dissipation amongst the sensor nodes to maximize the network lifetime. This is achieved by replacing the CH with low battery power with a proxy node and forming more clusters in the region relatively far from the BS. However, more clusters formed far from the BS increases energy consumption due to transmission of the data towards the BS by single hop communication. In both PEACH and EDACH, the authors used a threshold value to determine when the current CH becomes obsolete, which is simply calculated as:

$$E_{thres} = \frac{1}{q}\sum_{j=1}^{q} E_{CH_j}$$

where, q is the number of CH nodes in the network and E_{CH_j} is the energy consumed by j^{th} CH during one round of network operation. However, the calculation of the threshold value as an average energy consumption of all CHs in the network is not an effective approach, as all clusters do not expend energy at an equal rate and it also incurs a network-wide message overhead.

Li *et al.* propose the CREED [76] protocol, which combines the clustering technique with the Energy Directed Dynamic Sorting backup scheme (EDDS) to support quick recovery of CH failures. According to this scheme, each node in one cluster is selected as a CH in turn, based on only the highest residual energy, however this ignores the intra-cluster energy consumption. As a result, the protocol cannot guarantee minimum energy consumption. Furthermore, CREED considers that all nodes are location aware and adopts a backup scheme to the increase fault tolerance of the system. However, this scheme demands periodic broadcast of “alive” messages by a CH to inform non-CH nodes about its state, which increases messaging overhead.

EEHCA is a hierarchical clustering algorithm proposed in [77] to prolong network lifetime of WSN with location aware nodes. This paper introduced the backup CH for a cluster, which may take over the role of primary CH when the primary CH is destroyed or its energy reaches less than 30% of initial energy. Here, the backup CH selection is based on the nearest position to the primary CH. However, the position of the backup CH might increase the intra-cluster communication distances, causing more energy consumption while the member nodes communicate with the backup CH. Hence, this technique is not energy efficient. Moreover, a single backup CH cannot provide adequate fault-tolerance in the network.

A self-organizing Domatic Partition (DP) scheme is presented in [78], which is able to reduce the time and energy overheads of CH rotation, and thereby, enhances the network lifetime compared to existing clustering protocols. The rotation of the CH roles amongst nodes is targeted to achieve load balancing. Here, the problem of domatic partitioning [79] was achieved by two steps: clique packing and ranking. The goal of clique packing is to decompose network into cliques. In Unit-Disk-Graphs (UDG) [80], the nodes within a half radius circle with the head at the center form a clique. The location information obtained from GPS is used to define the ordering of the nodes to produce a ranking and assign the ranks to each node in the clique. The set of nodes with the same ranking across each clique forms a dominating set. Lastly, the rotation of the role of CHs periodically activates the dominating set through DP to obtain the clustering. This scheme, however, is unable to acquire a distinct rank for uncovered nodes and has not addressed the scheduling scheme.

A hierarchical multiple backup CH scheme is presented in [81], where all nodes know the coordinates of the base station and hence determine their position based on the approximate distance and angle information using their directional antenna. The optimum radius is then calculated and the given area is divided into clusters. Based on the distance, the first nearest node in a cluster acts as a primary or CH node, followed by the second, and third nodes, and so on. The backup CH replaces the primary CH in two cases: firstly, when the primary CH breaks down and; secondly, if the primary CH consumes 70% or more energy than its initial energy. Although the authors claim an increased network lifetime over LEACH, HEED and EEHCA, the inefficient selection of the backup CH and its switching time can raise the energy consumption in the cluster. Moreover, the scheme could not demonstrate an increase in the reliable transfer of data in the network.

This research does not investigate the location aware clustering techniques for several reasons. Wireless sensor nodes are usually tiny in size and very low in cost. Making a node location aware requires extra hardware (e.g. a GPS) embedded in the wireless sensor node, which makes it bigger in size. In addition, due to the shadowing affect of a GPS, it is not applicable to all terrains, especially not in the environments where sensor networks are usually deployed. Most sensor applications need to deploy the sensor node densely and in a large number (e.g. in the hundreds) in inaccessible terrains. Thus, GPS enabled sensor nodes involves a huge cost compared to location unaware sensor nodes. This cost may restrain wide-spread deployment of WSNs. Furthermore, it is likely that some of the nodes get destroyed at the time of deployment or are damaged by natural events or some other means. Therefore, using a GPS-enabled sensor is not a cost-effective solution for most sensor applications. The following section will provide a overview of the location unaware clustering techniques.

2.1.2 Location Unaware Clustering Techniques

It is a real challenge to develop a clustering algorithm when the sensor nodes in WSNs are unaware of their geographic locations. Many of the clustering initiatives in the literature have tried to achieve some performance metrics, such as energy efficiency, reliability, fault tolerance, and so on, for WSNs with location unaware nodes. As mentioned before, the main motivation of clustering a WSN considering location unaware nodes is to reduce the deployment cost; i.e. the cost of a sensor node. In this section, we discuss the location unaware clustering techniques that exist in the literature. As mentioned before, a variety of clustering techniques have been developed that place emphasis on a particular performance metric, such as energy efficiency, reliability, delay and message overhead. Therefore these can be classified into the following classes: (i) energy aware clustering, (ii) reliable clustering; (iii) delay sensitive clustering; and (iv) overhead message aware clustering techniques. These are described in the following sections.

2.1.2.1 Energy Aware Clustering Techniques

A number of energy-efficient hierarchical clustering algorithms have been proposed in the literature [12, 32, 14, 33, 82, 34, 35, 36, 83, 84, 85] to prolong the network lifetime. One of the pioneer WSN clustering techniques proposed by Heinzelman *et al.* [12] is the Low Energy Adaptive Clustering Hierarchy (LEACH). LEACH is developed mainly for periodical data gathering applications. A distributed algorithm is presented in LEACH to form clusters where nodes individually take decision instead of being centrally controlled by the BS. The operation of LEACH is divided into rounds, as shown in Fig. 2.3. Each round begins with a set-up phase when the clusters are organized, followed by a steady-state phase when data are transferred from the nodes to the CH and then to the BS. All nodes take part in selecting q number of CHs in each round. As the CH nodes consume more energy than member nodes, each node needs to take its turn in becoming a CH. Therefore, the algorithm distributes the energy load amongst all nodes in the network by randomizing the rotation of CHs, where the

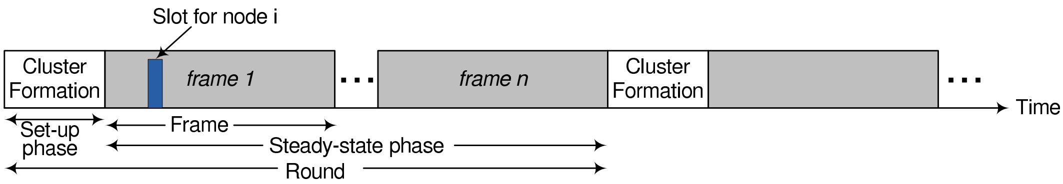

Figure 2.3: Time line of LEACH operation cycle.

selection of CH nodes is based on probability defined as:

$$P_i(t) = \begin{cases} \frac{q}{n-q\times(r\ mod\ \frac{n}{q})} & if\ C_i(t) = 1 \\ 0 & if\ C_i(t) = 0 \end{cases} \quad (2.2)$$

where r is the number of elapsed rounds and n is the total number of nodes. $C_i(t) = 0$ if a node already became a CH in the most recent $(r\ mod\ \frac{N}{q})$ rounds and is equal to 1 otherwise. q is the optimal number of CH nodes in the network. According to LEACH, each node chooses a random value between 0 and 1 and if the value is lower than the calculated probability, the node is elected as a CH node. A node that has not become a CH in a specific round will have a higher probability of becoming a CH in the next round.

The above choice of probability for becoming a CH is based on the assumption that all nodes start with an equal amount of energy. If nodes have different amounts of energy then the nodes with more energy should be CHs more often than the nodes with less energy, to ensure that all nodes die at approximately the same time. In this case, the probability of becoming a CH is a function of a node's energy level relative to the aggregate energy remaining in the network, rather than purely a function of the number of times the node has been a CH. Thus,

$$P_i(t) = min\{\frac{E_i(t)}{E_{tot}(t)}q, 1\} \quad (2.3)$$

where $E_i(t)$ is the current energy of node i at time t and $E_{tot}(t) = \sum_{t=1}^{N} E_i(t)$.

Once CH nodes are elected using the probabilities in (2.2) or (2.3), these nodes let all the other nodes in the network know that they are chosen to perform the role of a CH for the current round by broadcasting an advertisement message (ADV) using a Carrier-Sense Multiple Access (CSMA) MAC protocol [86]. Each non-CH node chooses its CH that requires the minimum communication energy, which is determined based on the RSS of the advertisement from each CH. For this, LEACH assumes symmetric propagation channels that are assumed to be error free. Thus, the CH advertisement with the strongest signal reception is considered the CH that requires the minimum amount of transmitted energy to communicate. In the case of a tie, a random CH is chosen. Soon after a node decides about its CH, it informs the CH node that it will be a member of that cluster by transmitting a join-request message (Join-REQ) to its chosen CH using the CSMA MAC protocol. Then the CH node sets up a TDMA schedule, as shown in Fig. 2.3, with a slot for node i and transmits this schedule to the nodes in the same cluster so that there are no collisions amongst data messages. The TDMA scheduling also allows the radio components of each cluster member node to be turned off at all times, except during their transmission time, thus reducing the energy consumed by the individual sensors. The cluster set-up phase completes after the TDMA schedule is known by all nodes in the cluster. Then the steady-state operation begins when the actual data transmission takes place. The TDMA time schedule is adopted among the relay CH and the member nodes to avoid collision, and the CH nodes communicate to the BS using a fixed spreading code and CSMA. Each CH assumes direct communication to the base station. A flowchart of the distributed cluster formation algorithm of LEACH is shown in Fig. 2.4. The authors also analytically

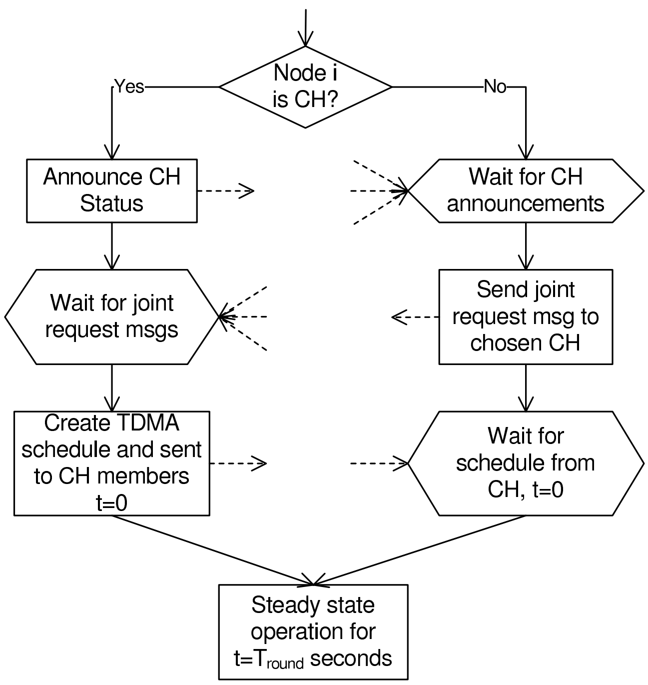

Figure 2.4: Flowchart of the LEACH clustering algorithm.

determined the optimum number of clusters assuming n nodes are uniformly distributed in a region. To do this they considered all types of energy consumption, such as data transmission, data reception, and data aggregation, and found that the optimum number of clusters is, $1 < q_{opt} < 6$. The simulation results for a WSN network with 100 nodes show that the optimum number of clusters is around $3 - 5$.

The radio energy dissipation model used in the LEACH experiment utilized a transmitter that dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics, as shown in Fig. 2.5. If the distance between the transmitter and the receiver is less than a threshold d_0, the free space (fs) model is used; otherwise the multi-path (mp) model is used. Thus, to transmit an l-bit message at a distance d, the radio expends

$$E_t = le_{elec} + l\varepsilon_{fs}d^2, \quad d < d_0 \tag{2.4}$$

or

$$E_t = le_{elec} + l\varepsilon_{mp}d^4, \quad d \geq d_0 \tag{2.5}$$

and energy required to receive l-bit message is,

$$E_r = le_{elec} \tag{2.6}$$

where, e_{elec} is the electronics energy, which depends on factors such as the digital coding, modulation, filtering and spreading of the signal; whereas the amplifier energy, $\varepsilon_{fs}d^2$ or $\varepsilon_{mp}d^4$, depends on the distance to the receiver and the acceptable bit-error rate. The LEACH protocol, however, has limited scalability and does not guarantee a good

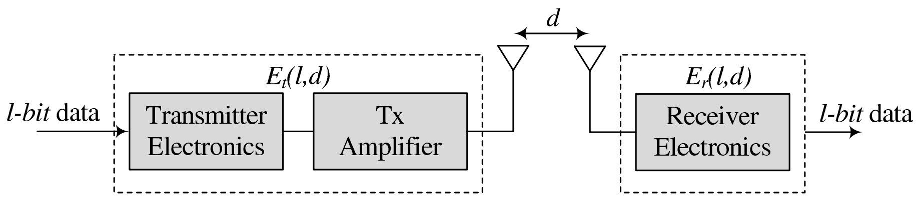

Figure 2.5: Radio energy model.

CH distribution. Also, random selection of CHs can result in the faster death of some nodes; consequently, their frequent failures result in a large re-clustering overhead. It generates clusters based on network size and does not work well in a dynamic network.

The LEACH algorithm allows only 1-hop clusters to be formed, which might lead to a large number of clusters [32] and longer range transmission from CHs to the BS.

Therefore, in [32], the authors proposed distributed algorithms for organizing sensors into a hierarchy of clusters, to minimize the energy spent in communicating information to the sink. Here, CHs collect the sensors' readings in their respective clusters and send aggregated data to the BS. Initially, each node announces itself as a CH with probability p to the neighbouring nodes within its communication range. These CHs are called the volunteer CHs. All nodes that are within z hops distance of a CH receive this announcement, either by direct communication or by forwarding. Any node that receives such announcements and is not itself a CH becomes a member of the closest cluster. If the CH announcement does not reach a node within a preset time interval t, which is calculated based on the duration for a packet to reach a node that is z hops away, the node will become a forced CH, assuming that it is not within z hops of all volunteer CHs. Here, forced CHs are nodes that are neither CHs nor belong to a cluster. The authors derived mathematical expressions for the values of p and z that achieve minimal energy consumption. However, minimizing the total energy consumption is not equivalent to maximizing coverage time, as the former criterion does not guarantee a balanced power consumption at various CHs [87].

To avoid the clustering overhead of LEACH, rather than forming multiple clusters, Power-Efficient GAthering in Sensor Information Systems (PEGASIS) [13] forms a number of chains from sensor nodes. The chain construction is performed in a greedy way, to minimize the energy consumption, which inherently supports multi-hop routing and helps achieve performance gain over LEACH. Either nodes can construct the chain, or the BS can compute the chain and broadcast this information to all sensor nodes. At the time of data gathering, each node receives data from its neighbour and aggregates with its own data and transmits to the other neighbor on the chain. Only one node is selected as a leader from that chain to transmit to the BS. The role of the leader changes in each round between the participating nodes of a chain. A token passing system is initiated by the leader node in each round to begin the data transmission from one end of the chain. As illustrated in Fig. 2.6, node M_3 is the leader of the chain. At first, node M_1 sends its data toward node M_3 after receiving a token from M_3. After receiving data from node M_2, M_3 node passes the token to node M_5 and thereafter, M_5 sends its data towards M_2. If a CH dies, the chain is reconstructed in the same manner to bypass the dead node. PEGASIS requires global knowledge of the network to form clusters, which introduces huge overhead. Moreover, PEGASIS introduces excessive delay for distant nodes on the chain and the single leader creates a bottleneck.

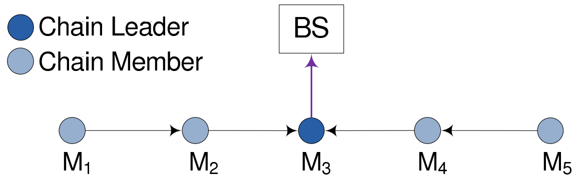

Figure 2.6: Token-based data passing approach.

Yu *et al.* [85] identified two major drawbacks in PEGASIS [13] and DEEC [88]. To prolongs the network lifetime by increasing the energy utilization of the network, a chain type structure was proposed in PEGASIS that requires global knowledge of the network topology and, as a result, the further nodes encounter bigger data delay. In the DEEC [88] protocol, CHs are elected by a probability based on the ratio between the remaining energy of each node and the average energy of the networks, which also requires an estimation of the total energy of the networks according to the network topology and needs to broadcast this to all nodes. To overcome the above drawbacks, an Energy Efficient Distributed Multi-level Clustering algorithm (EEDMC) [85] is proposed, which chooses CH candidates round-by-round based on the proportion between the remaining energy of each node and the average residual energy of its neighbouring nodes, and then determines the CH candidates with the minimum communication cost as its CH. The EEDMC constructs clusters at each round. Each sensor node saves the remaining energy information of its neighbouring nodes in a table. After the cluster formation, a CH is chosen from the CH set for communicating with the BS. Then, inter-cluster routing among the CHs is constructed for transmitting data to the BS by multi-hop routing. The CH nodes are organized into a chain, as shown in Fig. 2.7, and the CH node closest to the BS is chosen as the leader of the chain in each round. However, in this technique, the same set of CH nodes is used for relaying the multi-hop traffic, which introduces a hot-spot problem in the network that may lead to the sudden death of CH nodes.

Both LEACH [12] and [32] have investigated clustering protocols in the context of routing protocols or independent routing. A general distributed clustering approach, namely Hybrid Energy Efficient Distributed clustering (HEED) [14], was proposed, which considers a hybrid of energy and intra-cluster communication costs. Four pri-

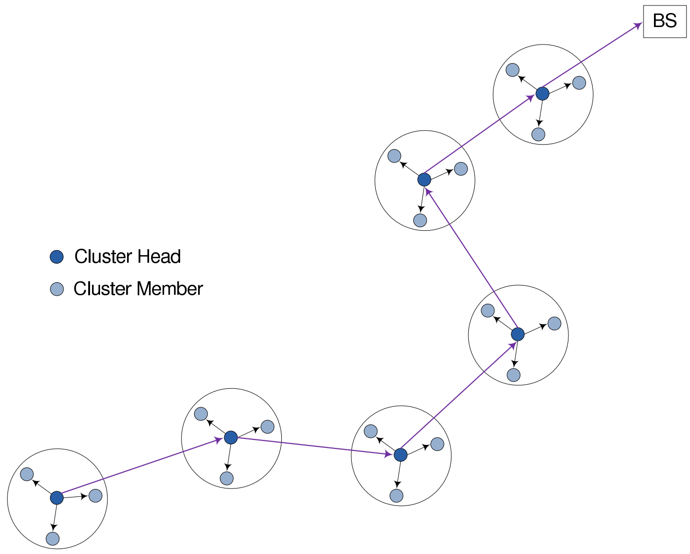

Figure 2.7: Formation of CHs chain by EEDMC algorithm.

mary objectives of the HEED protocol were: (i) prolonging the network lifetime by distributing energy consumption; (ii) terminating the clustering process within a constant number of iterations; (iii) minimizing the control overhead; and (iv) producing well-distributed cluster heads. Every node runs HEED individually and at the end of the clustering process, each node either becomes a CH or a child of a CH. HEED does not make any assumptions about the network, such as its density and size, and the protocol elects the CHs based on a node's residual energy defined as follows:

$$CH_{prob} = C_{prob} \times \frac{E_{RE}}{E_{max}} \tag{2.7}$$

where E_{RE} is the remaining energy of a node, E_{max} is the maximum or initial energy of each node and C_{prob} is the probability of a node becoming a CH.

Jang *et al.* [89] extended LEACH to propose a cluster-based routing scheme that selects the CHs based on the highest remaining energy and when the energy level drops below 50% of the initial energy. Member nodes select their CH based on the cost value, which is determined by the signal power and distance to the respective CH. The proposed algorithm only employed single hop communication and the data transmission takes place when the context satisfies the preset condition, otherwise nodes put themselves into the sleep mode for saving energy.

While residual energy is used as a primary clustering parameter, to further enhance the network lifetime, HEED also considers the intra-cluster communication cost as a secondary clustering parameter. This cost is a function of neighbour proximity or cluster density, which is used to determine the CH of a node, if it falls within the range of more than one CH. The intra-cluster communication cost is proportional to *node degree* if the intra-cluster communication power is fixed for all nodes, which also distributes the load among CH nodes and $\frac{1}{node\ degree}$ is used to form dense clusters. In addition to these, it is worth noting that inter-cluster communication has not been considered in the cost function. HEED also introduced the average minimum reachability power (ARE) to interpret the minimum power level required by all m nodes within the cluster range; i.e. $ARE = \frac{\sum_{i=1}^{m} MinPow_i}{m}$, where $MinPow_i$ represents the minimum power level required by a node n_i, $1 \leq i \leq m$, to communicate with a cluster head, CH_i.

The HEED clustering algorithm (Algorithm 2.1) needs a number of iterations to get a set of finally elected CHs, as described in Algorithm 2.1. In its initialization phase, the HEED protocol allows sensors to compute a probability of becoming CHs, proportional to its residual energy and to a pre-determined percentage of CHs; i.e. CH_{prob}. The value of CH_{prob} is not allowed to fall below a certain threshold p_{min}. Then, during a repetition phase, the sensor seeks the best CH for its joining. If no CHs are found, then the sensor node doubles its probability to become CH and broadcasts this again to its neighbours. This process terminates when this probability equals to 1 or it finds its suitable CH. HEED terminates within $O(1)$ iterations and achieves fairly uniform distribution of CHs across the network. However, HEED has not addressed the situation where the CH nodes die, which produces data loss. Also, the clusters generated by HEED are not well balanced and the cluster topology fails to achieve minimum energy consumption in intra-cluster communication.

Huang *et al.* [90] extended HEED to achieve a constant time clustering algorithm that can generate a small number of CHs in relatively few rounds, especially in sparse networks. They identified that the traditional clustering algorithm follows a general process to form a cluster. Each node sends an election message, including node ID and cost, to each of its neighbours and receives the information from its neighbours. Then the nodes check if there are some CH nodes within their neighbourhood. If CH nodes exist, then a node terminates its clustering algorithm and joins with its closest CH. Otherwise, it declares itself as CH. The time complexity of such clustering is $O(n)$ in the worst case and $O(logn)$ on average. The message complexity is $O(1)$ for one node

Algorithm 2.1 HEED clustering algorithm

Initialization:
  $S_{nbr} \leftarrow v:\ v\ lies\ within\ cluster\ range$
  $Compute\ and\ broadcast\ cost\ to\ \epsilon S_{nbr}$
  $CH_{prob} \leftarrow max(C_{prob} \times \frac{E_{RE}}{E_{max}}, p_{min})$
  $is\_final\_CH \leftarrow FALSE$
repeat
    $If((S_{CH} \leftarrow v:\ v\ is\ a\ cluster\ head) \neq \phi)$
      $my\_cluster\_head \leftarrow least\_cost(S_{CH})$
      $If(myclusterhead = NodeID)$
        $If(CH_{prob} = 1)$
          $Cluster\_head\_msg(NodeID, final\_CH, cost)$
          $is\_final\_CH \leftarrow TRUE$
        $Else$
          $Cluster\_head\_msg(NodeID, tentative\_CH, cost)$
    $ElseIf(CH_{prob} = 1)$
      $Cluster\_head\_msg(NodeID, final\_CH, cost)$
      $is\_final\_CH \leftarrow TRUE$
    $ElseIfRandom(0,1) \leq CH_{prob}$
      $Cluster\_head\_msg(NodeID, tentative\_CH, cost)$
    $CH_{prev} \leftarrow CH_{prob}$
    $CH_{prob} \leftarrow min(CH_{prob} \times 2, 1)$
until $CH_{prev} = 1$
Finalization:
  $If(is\_final\_CH = FALSE)$
    $If((S_{CH} \leftarrow v:\ v\ is\ a\ cluster\ head) \neq \phi)$
      $my\_cluster\_head \leftarrow least\_cost(S_{CH})$
      $join\_cluster(cluster\_head\_ID, NodeID)$
    $ElseCluster\_head\_msg(NodeID, final\_CH, cost)$
  $ElseCluster\_head\_msg(NodeID, final\_CH, cost)$

and $O(n)$ for the networks. The protocol proposed by Huang *et al.* executes the core algorithm [91] in the first round, where each node checks if its cost is the least among its neighbours (including itself). If a node finds its cost as is at lowest, it sets itself as a core head. Otherwise, after the core election, the CH election phase takes place on all nodes except the non-core nodes. The proposed algorithm adds two more steps to HEED to eliminate a large quantity of nodes, and selects only potential candidates to participate in the CH election. Therefore, it is more energy efficient than the HEED clustering algorithm.

Mandala et al. [92] identified that energy dissipation in the existing cluster-based protocols (e.g. LEACH, and HEED) is unbalanced in the entire network. This is due to two popular strategies of routing data from CHs to the BS: direct connection and shortest path routing. As a result, part of the network dies earlier than others. To overcome this problem and enhance the network lifetime, they proposed the Even Energy Dissipation Protocol (EEDP) [92]. EEDP is a energy efficient cluster-based data gathering technique that balances the traffic load and thus avoids the *hot spot* problem. The basic idea of EEDP is to organize CH nodes into several parallel chains. Each chain uses a rotation scheme to balance energy consumption among CHs. The intra-chain routing scheme is similar to the shortest path routing, where each node forwards its data and its predecessors' data to its successor and the last node forwards the data to the BS. Although this protocol tries to minimize the energy consumption of the network, the energy efficient path cannot always guarantee a reliable routing path.

Cao *et al.* [82] identified that, due to the randomness in production of CHs, LEACH is not as load-balancing as expected. To eliminate this problem and prolong the system lifetime, they proposed a distributed algorithm based on an adaptive back-off strategy that evenly distributes energy load amongst the sensor nodes. The algorithm operates in rounds, where each round begins with a cluster formation phase. In the cluster formation phase, nodes initially remain in the waiting mode. Every node i maintains a variable x_i, which is assigned a random value from 0 to 1. Each node i waits for a initiator timer according to an exponential random distribution; i.e.

$$x_i = \lambda_i e^{-\lambda_i t_i} \tag{2.8}$$

where, $\lambda_i = \lambda_{min} + (\lambda_{max} - \lambda_{min}) \frac{E^i_{RE}}{E_{max}}$.

Here, λ_{min} and λ_{max} are pre-determined parameters. The more remaining energy a node possesses, the shorter will be its waiting time, and greater the chance of this node becoming a CH. However, the random selection of the value of x_i in the back-off strategy can ruin the intention of selecting energetic nodes as CHs, resulting in inefficient energy consumption.

When the timer fires, node i elects itself as a CH and broadcasts this information. Upon receiving the broadcast message from node i, node j stops the timer and decides to join i. When node j decides to join a cluster, it broadcasts its joining information and terminates the algorithm. The proposed distributed clustering algorithm ensures that the elected CHs are well distributed. The back-off strategy outperforms both LEACH and HEED by saving energy from iterative message broadcasting and prolongs the network lifetime. Although this algorithm selects better CH nodes, like LEACH, it considers direct communication (single hop) between the CH node and the BS, which consumes more energy.

While existing popular clustering algorithms, such as HEED, consider the residual energy of a node and node degree, Anker *et al.* [35] introduced a clustering algorithm, which not only considers local properties but also takes into account joint characteristics of a group of nodes, such as link quality and topology information. The algorithm also maintains a small constant message and time overhead, leading to a considerable increase in network performance and balanced power consumption amongst the nodes. In their algorithm, the network lifetime is tightly coupled with the network performance. The algorithm proposed by Anker *et al.* is a fully distributed inference clustering algorithm based on belief propagation (BP) [93], which is used for efficiently solving inference problems. The protocol selects CH nodes that (i) minimize the total transmission energy over all nodes in the selected path; and (ii) balance the load among the nodes. However, these two requirements may contradict if a longer path, which consumes more energy, is selected over a shorter path, which consumes less energy, to avoid energy drainage at some nodes. The BP algorithm achieved an improved network lifetime, data transmission time and rate compared to the HEED scheme. However, the protocol suffers from the message overhead of sharing link quality and topology information amongst the nodes. Compared to the HEED clustering algorithm, BP suffers from more overhead during the clustering process. The increase of the rate of overhead message is higher than that of HEED; in other words it is less scalable than HEED.

In [94], the authors presented a single-level aggregation and proposed an Energy-Efficient Protocol for Aggregator Selection (EPAS) protocol. Then, they generalized this to an aggregation hierarchy and extend EPAS to a Hierarchical EPAS. The protocol assumes that nodes are uniformly distributed over a region and sensors send packets to their respective CHs using multi-hop paths. For a given number of sensors, compression ratio, deployment area, characteristic distance, and other network parameters, they could calculate the optimal number of aggregators, which can minimize the energy consumption of the network. They also presented a more general framework that organizes the aggregators into a hierarchy. A subset of Level 1 aggregators forms Level 2 aggregators. A similar process continues at the next highest level until the sink becomes the final aggregator. The optimal number of aggregators in each level was also calculated in hEPAS, which is an extension of EPAS. Simulations of energy consumption in networks with different numbers of levels and aggregators at each level showed that the total energy consumption reduced significantly by employing the proposed protocols. However, a comparison with any existing protocol was not given in the paper.

Xia *et al.* [34] argued that existing WSN clustering algorithms commonly do not consider the similarity of sensed data as an important clustering criterion. As a result, they are not fully capable of dealing with the WSN energy conservation challenge. Therefore, they proposed the Local Negotiated Clustering Algorithm (LNCA) [34], which attempted to minimize the overall energy consumption of the network by employing the similarity of nodes' readings as a criterion in cluster formation. LNCA reduces the data reporting related traffic and achieves considerable improvements over LEACH.

According to [36], the previous research mainly focused on balancing energy consumption among cluster members and they did not consider energy consumption among CHs while conserving node energy and prolonging the lifetime of the network. Therefore, a Single-Hop Active Clustering (SHAC) algorithm is proposed in [36] that has three parts. Firstly, CHs are selected based on an average energy factor to balance the remaining energy of the entire network and to improve the energy efficiency of the network. Secondly, a cost function is proposed to achieve the energy efficiency of each node. Finally, SHAC presents an active clustering algorithm for single-hop homogeneous networks. At first, a tentative CH is selected based on the policy that the more remaining energy of a node, the greater the probability of this node selecting as a CH node. After that according to the cost function, the tentative CH nodes select the final CHs according to the number of nodes adding to that CH. Lastly, the final CHs broadcast their information around the nodes. As LEACH does not consider the remaining energy, the SHAC protocol could achieve 30% more lifetime as compared to the LEACH.

As the LEACH protocol did not consider the heterogeneity of nodes in terms of their initial energy, the network energy consumption was not optimized. Therefore, Kumar *et al.* [83] introduced a Energy Efficient Heterogeneous Clustered (EEHC) protocol, the goal of which is to increase the lifetime and stability of the network in the presence of heterogeneous nodes. The proposed scheme is introduced where CH election of the network is performed based on the weighted election probabilities of each node according to the remaining energy in each node. This assumes that all nodes are uniformly distributed and inter-cluster communication takes place directly between each CH and the BS, which are suitable for most WSN applications. Therefore, the protocol could not increase the network lifetime more than 10% as compared with LEACH.

The conventional WSN clustering approach encounters a unique challenge due to the fact that CHs, which by default act as communication centers, tend to be heavily utilized and quickly drained of their battery power. Therefore, the Dynamic Transmission Range Adjustment Protocol (DTRAP) [84] is proposed, which introduces a re-clustering strategy and a redirection scheme for cluster-based WSNs, to reduce the power consumption problem and to maintain the merits of a clustering approach. The DTRAP can adjust the transmission range of each node to keep its neighbours nearly constant. In the scheme, the network area is partitioned into clusters at the initial phase using any clustering algorithm. Then a node with higher remaining energy is chosen to act as a CH for that cluster. However, selecting a CH based on maximum remaining energy does not ensure minimum energy consumption in the cluster, as the position of the CH may not be at the center of the cluster. Furthermore, the authors assumed that the nodes are capable of varying their transmission range in order to directly communicate with any other node in the network, which may not be sufficient enough to maintain the connectivity for the entire network.

The main reason for an energy imbalance is the unequal distribution of the communication load [95]. Therefore, unequal clustering [33, 96, 97] has been studied to tackle the problem of unequal energy consumption in the clustered WSN. In EECS [33], a distance-based cluster formation method is proposed to produce clusters in unequal size where nodes are dispersed uniformly in the sensory field. Clusters further away from the BS have smaller sizes, thus some energy could be preserved for long-haul data transmission to the BS. However, CHs are chosen here based only on residual energy and a less energy consuming inter-cluster multi-hop communication technique is not considered. However, this increases the probability of creating a *hot spot* problem due to the excessive usage of CH nodes closer to the BS, receiving and aggregating data from more member nodes and relaying more traffic from underneath the CH nodes. To address this, the Energy Efficient Multi-hop Routing protocol for wireless sensor networks (EEMR) [96] was introduced for an uneven clustering mechanism (Fig. 2.8) and inter-cluster multi-hop routing selection mechanism, assuming that nodes are uniformly distributed over a vast field. Clusters that are closer to the BS have a smaller cluster size than those further from the BS, thus they can preserve some energy for the purpose of inter-cluster data forwarding. EEMR improves the network lifetime over HEED. However, the uneven cluster size, consisting of nodes with different residual energy, can cause an energy imbalance in the cluster, resulting in the faster death of some nodes.

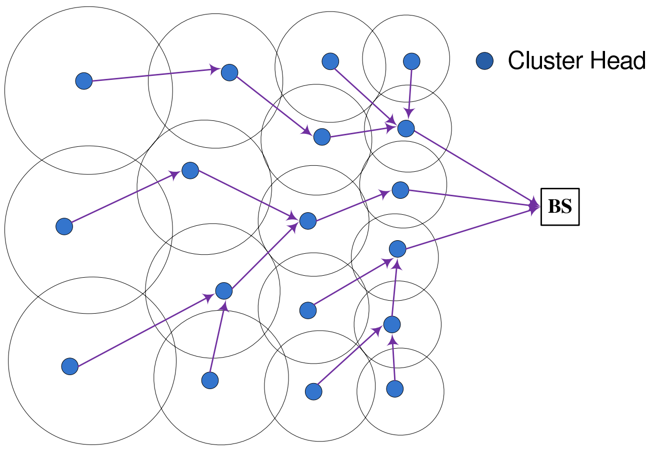

Figure 2.8: Example of uneven clustering for wireless sensor network.

To increase the WSN's lifetime and scalability, the Dynamic Multilevel Hierarchal (DMH) clustering with adaptive feature is proposed [98], which can vary the topology architecture according to traffic patterns. The size of the cluster, number of nodes in a cluster, and the level of hierarchy of a cluster varies according to the state of the system. In this approach to energy efficient clustering, CHs are selected periodically, based on a node's remaining energy and node degree. Initially, all the nodes send their remaining energy and node degree information to their neighbours based on which nodes are contending to become the CH. The winner node sends one confirmation signal and all the other nodes in closer vicinity send joining replies to this signal. Another design criteria is to create smaller sized clusters near the BS and to increase the cluster size proportionately to the distance of a cluster from the BS. As with EEMR, this strategy is used to deal with the unequal energy consumption nature of CH nodes, as CH nodes closer to the BS need to utilize more energy for relaying inter-cluster traffic than CH nodes located further from the BS. In addition, in DMH clustering, multilevel CHs are also selected dynamically according to varying traffic properties.

The proposed approach shows superior performance over LEACH and HEED for dynamic traffics. To solve the *hot-spot* problem caused by multi-hop forwarding in the layers closer to the BS, Zhao *et al.* [97] proposed an unequal layered clustering technique for a large scale WSN. According to this technique, layers closer to the BS have smaller width than those far away from the BS, so the CHs closer to the base station can preserve more energy for handling inter-cluster data traffic.

Research on the routing of sensor data mostly focuses on energy awareness to maximize the lifetime of the network. The transmission of video and imaging data requires the consideration of QoS in sensor networks, which increases the difficulties of achieving energy efficiency. Therefore, a QoS-aware hierarchical clustering protocol [99] is proposed, which extends the routing approach in [100] and considers only the end-to-end delay for real-time transmission of video and images. The protocol looks for a delay constrained path with the least possible cost based on a cost function defined for each link. The function captures the nodes remaining energy, transmission energy, error rate and other communication parameters. Alternative paths with bigger costs are attempted until one, which meets the end-to-end delay requirement and maximizes the throughput for best effort traffic, is found. This protocol performs well with respect to the delay constraint. However, it does not provide flexible adjustment of bandwidth sharing for different links.

Shu *et al.* [87] tried to maximize the coverage time of the network by balancing the power consumption of different CHs. Here, coverage time is defined as the time until one of the CHs runs out of powers resulting in an incomplete coverage of the sensing region. To achieve balanced power consumption, two mechanisms were proposed: the routing-aware optimal cluster planning and the clustering-aware optimal random relay. The second scheme is essentially a inter-cluster communication strategy that presents optimal power allocation strategies to achieve the end-to-end inter-cluster path reliability. According to this approach, a CH probabilistically chooses to either relay the traffic to the next-hop CH or to deliver it directly to the sink. Analysis shows the benefits of the proposed schemes in terms of prolonging the coverage time of the network.

A decentralized algorithm, the Clustering Algorithm via Waiting Timer (CAWT) for organizing sensor nodes into clusters is presented in [101], which does not require the nodes' location information a priori. In this technique, the sensors that have many neighbours are good candidates for forming new clusters. On the other hand, nodes with few neighbours should choose to wait. Each sensor uses a random waiting timer and if the timer expires, then the node declares itself as a CH. If the sensor node discovers a new neighbour, it shortens its timer. However, if one of the neighbour node declares itself as a CH, then the node immediately cancels its own timer and joins the neighbouring CH. Here, each sensor updates its neighbour information and decreases the random waiting time, where the formula for updating the random waiting time of sensor j is

$$WT_j^{(x+1)} = \gamma WT_j^x$$

where, T_j^x is the waiting time of sensor j at time step x and $0 < \gamma < 1$. When the random waiting time expires ($WT_i = 0$) and none of the neighbouring nodes become members of a cluster, then sensor node j can declare itself as a CH node. However, due to ignoring the channel conditions, connectivity and energy level of neighbouring nodes, this algorithm cannot achieve energy minimization in the network.

Alongside these cluster-based routing protocols, several other algorithms address congestion and interference aware routing in wireless sensor networks. The IFRC proposed in [102] uses an exponentially weighted moving average of the instantaneous queue length as a measure of congestion. Each node calculates this average and the node is said to be congested if it exceeds a threshold value. This congestion value signals to other nodes to adjust their data rates. The proposed technique can reduce packet loss rate, however, it does not ensure energy efficiency and end-to-end reliability. The SAR [56] enabled a table-driven multi-path routing approach in order to achieve energy efficiency and fault tolerance. However, there is high overhead in maintaining tables and states at each sensor. While much of the recent work in WSN routing protocols has focused on the shortest and most energy efficient path, less attention has been paid to the discovery of high-quality paths in terms of energy efficiency, link quality and congestion.

Su *et al.* [103] referred to that fact that a simpler, but sub-optimal scheme, was developed in [1], where nodes employ mixed communication modes, single-hop mode and multi-hop mode, periodically. Although a mixed communication mode can better balance the energy load efficiently over WSNs, the authors of [1] did not obtain the optimal communication range for the multi-hop mode, which is a critically important parameter for the mixed communication mode scheme. Moreover, in their analytical model, they only considered the grid deployment without considering the random deployment. To solve this problem, Su *et al.* [103] derived an optimal communication range and optimal mixed communication mode that maximizes the network lifetime. Here, mixed communication modes means that the member nodes can communicate with CHs in either a single-hop or multi-hop mode. This assumes a heterogeneous cluster-based network with two types of nodes: powerful CH nodes and basic member nodes. The protocol assumes that in each round, the CHs send the aggregated data to the mobile base station: e.g. an aircraft or a satellite. It is observed that in the multi-hop mode, nodes closer to the CH consume more energy due to relaying more traffic than the outer nodes. On the other hand, in the single-hop mode, member nodes closer to the CH dissipate less energy than those further away from the CHs. To overcome this problem, the proposed model employs a mixed mode, where member nodes use a single-hop communication mode in some rounds but a multi-hop communication mode in the other rounds. The optimal value of the parameters to measure how often the single-hop mode is to be used has been derived. Developing the analytical models, the optimal transmission range has also been derived numerically. According to this protocol, the CH and member nodes' deployment in the WSN follow two different distribution according to two independent spatial Poisson processes. However, simulation results indicated that the deployment of CHs in high density is not helpful in prolonging the network lifetime.

Using the Power Efficient Data gathering and Aggregation Protocol (PEDAP) [104], all nodes in the network can be constructed as a minimum spanning tree, however the protocol has difficulties in handling dead nodes in time. To deal with this problem, a

Cluster-based Multi-path Routing Protocol (CLBM) [105] is proposed, which extends the lifetime of sensor networks by improving load balancing in WSNs. CH nodes, particularly those that are closer to the BS, have more data traffic and therefore, deplete energy more easily. To solve this problem, this protocol adopts frequent replacement of the CH nodes to achieve load balancing. The CLBM protocol divides nodes into two types: cluster routing nodes and multi-path routing nodes. Here, nodes play the role of a multi-path routing node when their distance from the BS is less than a preset parameter d and does not participate in the cluster formation process, and the nodes whose distance from the BS is larger than d will be the cluster routing nodes. The nodes are clustered using the LEACH clustering protocol and then form a minimum spanning tree in a cluster. After that, the CHs are selected according to their remaining energy and the distance between them and the event center area. Cluster nodes select the nearer multi-path routing nodes whose distance are less than the distance between the CH and the BS by multi-path routing, and then randomly select a node to be put into the next-hop routing table. Member nodes of a cluster re-select a CH node based on the remaining energy and the nearest distance between the node and the event center area. The CLBM shows an effective reduction in the network load of cluster nodes and solves the energy consumption problems brought about by the CH nodes.

Radio power control for single-hop and multi-hop transmission is one of the methods that can be applied to reduce the power consumption. A number of energy models for sensor nodes are proposed in the literature [106, 12]. Zhu [107] proposed an energy consumption model for sensor nodes based on the characteristics of the radio transceiver. The then used the parameters of actual sensor node devices to determine the optimal range that maximizes the transmission energy efficiency. The optimal transmission range were also investigated for multi-hop transmission and the numerical results are presented to compare the energy efficiency performance. The numerical results show than an increasing number of hops does not necessarily improve the energy efficiency of the network. The problem of QoS routing is presented in [108], where data is transmitted from a source node to a destination node via multiple hops. To accomplish this, route discovery is necessary, which depends on factors like the physical and link layer designs of the underlying wireless networks and transmission errors due to channel fading [109] and interference. To calculate the link metric, this paper presented the decomposition queuing approach and incorporated this into the route discovery process of the QoS routing algorithm. The numerical results proved that the proposed framework is capable of finding a feasible route in the network if it exists.

Previous inter-cluster backbone tree construction algorithms, such as the Hierarchical Cluster-based Data Dissemination (HCDD) [110] and Multi-cluster, Mobile, Multimedia radio network (MMM) [16], were designed without considering the appropriate factors, such as the residual energy and node degree of a node for WSNs. As a result, these algorithms causes backbone nodes to consume energy quickly, causing a disconnected network. Therefore, a stable backbone tree construction algorithm is proposed in [111] for managing multi-hop communication in a clustered WSN. To increase the network lifetime, nodes with higher energy or degree are selected as CH nodes to create a stable backbone. The backbone nodes can reduce the communication overhead, such as control traffic, and minimize the number of active nodes. The proposed method also balances energy consumption by distributing the traffic load amongst nodes around the CH. However, member nodes are considered to communicate with the CH by multi-hop communication. As a result, nodes around the CH also consume more energy to forward packets, which demands another construction of the intra-cluster tree that has not been addressed in the paper.

The reliability of routing in WSN is significant in certain applications. Most existing routing protocols use multi-paths to improve routing reliability. However, multi-paths waste a large amount of energy to obtain redundancy. Therefore, this cannot be a good option for limited energy sensor nodes. Du *et al.* [112] identified this issue and proposed a Clustering-based Reliable Multi-hop Routing (CRMR) algorithm, which adopts a mechanism of multiple BCHs to extend the lifetime of clusters so that it decreases the energy consumption for reconstructing clusters. The algorithm overcomes the randomicity of selecting CHs and ensures well-proportioned clusters. Instead of preserving multiple backup paths, this protocol uses BCHs and gateways to achieve reliability of routing. The algorithm shows good performance on both routing reliability and energy consumption in the simulation results.

All the clustering techniques described in this section have placed emphasis on energy efficiency for organizing and forming the cluster hierarchy. However, they do not consider reliability as a prime factor in determining the cluster formation. There are a few such techniques available in the literature and these will be articulated in the following section.

2.1.2.2 Reliable Clustering Techniques

Due to the need to collect data without loss from nodes by many applications in WSNs, researchers have looked at factors that affect reliability and searched for efficient combinations of the possible options in their work. End-to-end re-transmission, which is used in the Internet for reliable transport, becomes very inefficient [38] in WSNs, as wireless communication and constrained resources pose new challenges. Information redundancy, like re-transmission and erasure codes, can be used to achieve reliability in a WSN. A number of algorithms were proposed [37, 38, 39, 40, 41, 42, 43] and implemented for multi-hop communications in WSN to achieve reliable transport for sensor networks. Some of these algorithms, which involve location unaware sensor nodes, are discussed below.

Wan *et al.* [37] stated that existing WSNs are application-specific and are typically hardwired to perform a specific task efficiently at low cost; however, there is an emerging need to be able to re-task or re-program groups of sensors in the WSN on the fly. An example of such a situation is disaster recovery. Reliable point-to-point communication is well understood in conventional IP-style communication networks, where nodes are identified by their endpoints. However, this kind of scheme (e.g., XTP [113], and SRM [114]) cannot be efficiently applied to WSNs, mainly because of the unique communication challenges presented by WSNs. These challenges include the need to support wireless multi-hop forwarding, cluster-based communications, application-specific operations, a lack of clean layering for the purposes of optimization, and so on. Therefore, Wan *et al.* [37] proposed the Pump Slowly, Fetch Quickly (PSFQ) protocol that investigates the problem of re-tasking a WSN reliably; they used the hop-by-hop recovery technique with caching at intermediate nodes, as opposed to end-to-end recovery. The proposed PSFQ outperforms the SRM in terms of communication overhead, error tolerance and delivery latency.

Kim *et al.* [38] observed that the PSFQ [37] identified the hop-by-hop recovery is very important for achieving reliability and considered only different re-transmission or repair options and used simulated data. However, Kim *et al.* added the very effective options of erasure coding and an alternate route for providing reliability. They also considered link level re-transmission and a route fix solution to handle the data loss. These options were implemented and evaluated in a test-bed where the experimental results achieved more than 99% reliability with low overhead. According to the experiment, the link level re-transmission handled link failure and contention very efficiently. The route fix solved the stable routing table problem providing a quick adaptation to link failure. Both link level re-transmission and the route fix occurs on demand and packet re-transmission takes place only when necessary.

As energy efficiency and reliability in the WSN depends on the features of each layer, such as the physical layer (i.e. power control), the MAC layer (i.e. re-transmission control) and the network layer (i.e. routing protocol), Kwon *et al.* [39] adopted a cross-layer strategy. To solve this problem, they decoupled it into sub-problems of each layer and proposed the optimal algorithm as well as an alternative heuristic algorithm with lower complexity for each sub-problem. Through simulations they showed that a trade-off between the network lifetime maximization and the reliability constraint could be achieved by combining the proposed algorithm at each layer. According to this, to minimize energy consumption and interference, only the sending and receiving nodes remain awake in each time slot, while other nodes stay in the sleeping state. The reliability in this work is obtained only through the power control and without re-transmission of the lost packet. Therefore, the transmission power is adapted by each node according to the channel gain. Simulations confirmed that the combination of power control, routing optimization and retry limit control can prolong the network lifetime over the non-optimal algorithms.

Some empirical and theoretical studies [115, 116] have shown that in a real WSN, links are unreliable. Particularly, in dense deployments, a large number of links in the sensor network (even higher than 50%) can be unreliable. Obviously, unreliability is one of the inherent properties of low-power wireless links. A number of efforts [117, 118, 119] to tackle the issue of the unreliability of wireless links focus only on the optimization of a single link. However, a limited performance gain could be obtained by optimizing a single-link. Although the ability of a single node is limited, the ability of multiple nodes in cooperation may be huge. Therefore, the idea of using multiple nodes to receive packets simultaneously and relay packets competitively has been presented in [40], which describes a nodes-cooperation strategy called Set Transfer. The potential of sensor node broadcast is that it allows all neighbours to receive and process packets simultaneously. Instead of one node, Set Transfer uses a set of nodes to receive and relay packets, which are comprised of two sets: one is called *Set Receiving*, while the other is *Set Relaying*. As illustrated in Fig. 2.9, the source node sends the packets to set M_1 and set M_1 uses Set Receiving to receive packets and uses Set Relaying to relay packets to set M_2. Again, set M_2 receives and relays the packets to M_3, and so on. Thus, through z hops, the packets reach to the destination node at the set M_z. Reception of data packets by multiple nodes also consumes lot of energy, which may increases the energy consumption by a huge amount. Although the simulation results show improvements in throughput and energy efficiency achieved by the nodes-cooperation strategy, a comparison with other reliable transmission techniques was not given in this paper.

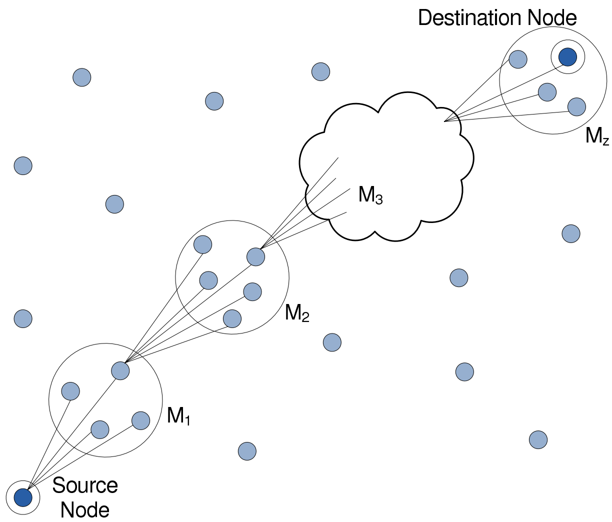

Figure 2.9: Set Transfer

A framework of a Hybrid Reliable Routing Technique (HRR) is presented in [41], which efficiently identifies CHs. The remaining nodes join CH nodes based on the energy availability factor of the neighbouring node to ensure services for an extended period. The concept of Graph Theory [120] is used to identify the CHs that form a Dominating Set (DS). The characteristics used to identify the CH are: maximizing cluster sizes while maintaining full coverage, minimizing cluster overlap, creating a highly uniform and balanced clustering, and performing routing through the CHs to the BS that is expending the least energy. According to the paper, if the energy of any

CH falls below a threshold value, it hands over its role to a node that has got maximum energy, thereby providing reliable transmission. It is also pointed out that the energy available in the CHs forms the bottle neck during routing. To solve this issue this paper suggested that routing is carried out by identifying the maximum energy possessing path. However, this technique does not guarantee overall energy minimization in the network.

Sensed data are often stored in the node before they are collected by a CH or relay nodes. If a node fails then it may cause a massive data loss. Therefore, to minimize the data loss caused by the delayed report, Kim *et al.* [42] proposed the data backup scheme that assumes that nodes are aware of their geographic location. The proposed scheme backs up a single data to multiple nodes that exist in a one-hop distance from the source node. Then multiple backup nodes distributively report their backup data to the BS instead of the source node. When a node senses data, it simply broadcasts a backup message without targeting any specific neighbouring nodes. The neighbouring nodes that receive the backup message, store it and calculate the backup suitability for the given source node. The backup suitability is calculated based on the residual storage, residual energy and distance from a source node. After that, they report the backup suitability information to the source node. Once the source node receives all the reports from its neighbouring nodes, it prepares a list of neighbouring nodes according to backup suitability in descending order. The highest X nodes in the list are selected as storage for data backup and this selection is broadcasted to the neighbouring nodes from the source node. On the other hand, the neighbouring nodes that are not selected as backup storage flush their storage. The selection of backup nodes is illustrated in Fig. 2.10. The data backup process is repeated every time a node senses data. To minimize the data loss, the proposed solution sacrifices the nodes' precious energy through excessive messaging and processing overhead.

The backup clustering technique can effectively increase the reliability of the network by minimizing the re-clustering time and providing the fault tolerance to the system. As CH nodes consume more energy than member nodes, all clustering protocols employ frequent re-clustering to balance energy consumption across the network. This frequent re-clustering process, which causes a major overhead of energy and time, could be delayed by efficient use of a backup clustering technique. Moreover, due to

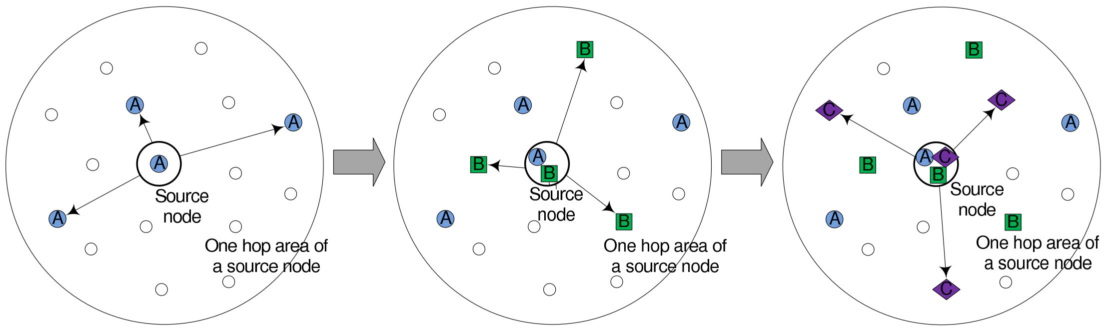

Figure 2.10: The data backup processes after sensing the data (X=3).

excessive use, a CH node may break down suddenly due to fast depletion of its energy in a certain context. As a result, part of the WSN becomes inaccessible, which incurs data loss in the network. As far as we are aware, only one backup clustering technique [55] exists in the literature that enhances the reliability of a WSN. This is described in the following.

Hashmi *et al.* proposed [55] a BCH scheme for a WSN with location unaware nodes. This scheme reduces the loss due to the failure of a CH in any existing clustering protocol by selecting a backup CH. If a CH node starts to die, the coverage of that cluster is lost, leaving that part of the region un-monitored. Even if the CH nodes are rotated, until the next rotation the cluster in question will be out of CHs and will lose coverage. To overcome this problem, they used single and double BCHs for those CHs whose residual energy level is close to depletion and are expected to die before the next rotation. In their approach, they select a BCH for those CHs whose remaining energy level is already at a threshold. Initially, during the setup phase, only CHs of the cluster are chosen and after that the BCH is selected depending on the need. The node with the highest remaining energy in the cluster is chosen as the BCH node. This assumes that a CH node consumes $E_{CHcost/rnd}$ energy on average. Any sensor node, after being selected as a CH, will be eligible to have a BCH if $E_{res} \leq E_{CHcost/rnd}$ where, E_{res} is the residual energy of a node at the beginning of any round. In this case, when the BCH nodes also die, then data loss occurs at that time, but this loss will be much less than without a BCH. To cope with this situation, a Double Backup CH (DBCH) is also proposed, which takes the place of the BCH when a BCH is also expected to die sooner. The protocol was tested to observe the network performance on a WSN using the LEACH-C protocol. It showed more data transfer reliability by reducing data loss due to the death of CH nodes. Even though this scheme increases data transfer reliability to some extent, it decreases the network lifetime compared with LEACH-C. This is due to the selection of the BCHs based on the maximum remaining energy and ignoring the minimization of the intra-cluster communication cost and switching energy.

Xiong *et al.* [121] identified that randomization of the selection of CHs in LEACH causes the cluster size to be different, and this causes uneven energy consumption of the nodes. As a result, few nodes die prematurely. They proposed the energy aware selection of the CH, where nodes that have a lot of surplus energy act as CHs for as long as possible. In the network operation or cluster maintenance time, a rotation of the CH role amongst all nodes is proposed for distributing the nodes energy consumption. Thus, the network operation round could be increased and the cluster setup time could be minimized in the entire network life-span. Three parameters, SB, SA and $Tround$, would be used in the CH scheduling process, where SB is a network parameter whose lowest value equals the frame size dividing the channel rate; SA is a cluster parameter showing the duration of some node acting as a CH node in the cluster; and $Tround$ shows that the round duration is determined a priori. A node determines its times to perform as a CH node according to the value of $Tround/SB$, giving all nodes equal time to act as a CH node. The protocol is based on an assumption that all nodes could reach the base station by one-hop communication, which is not suitable in a real-world application. For a large WSN, the CH located far from the BS will require too much energy to communicate with the BS in the first place. Moreover, although the rotation of the role of CH amongst all nodes within a cluster can balance energy consumption, the overall energy consumption of the network will increase significantly as the location of the new CH node will not guarantee the minimum intra-cluster communication cost.

2.1.2.3 Delay Sensitive Clustering Techniques

Cluster-based routing protocols need to ensure that the data packets are delivered to the BS correctly and without any delay. In addition to energy efficiency, QoS metrics, such as end-to-end delay, have been taken into account in some protocols [44, 46, 47]. This section discusses the existing routing protocols that consider delay as a QoS routing parameter.

Chen *et al.* [44] presented an efficient scheduling for a delay-constrained Code Division Multiple Access (CDMA) [63] WSN. The authors first determined the optimum schedule for the intra-cluster communications, which minimizes the total transmit power of the sensor nodes. Then they considered the inter-cluster communications where CHs are equipped with two antennas and use Alamouti space-time coding [122] to achieve the Transmit Diversity (TD). When applied to the inter-cluster communications, the proposed scheduling protocol provided a near-optimum solution, with a modest sacrifice in performance. The numerical results showed considerable power savings with respect to a TDMA type scheduling scheme.

In a clustered WSN, TDMA scheduling for intra-cluster communication is a widely known strategy. Instead of only allotting a slot for intra-cluster communication, Shi *et al.* focused on the more challenging inter-cluster slot assignment in [46]. They addressed the scheduling problem in a clustered WSN and proposed a nonlinear cross-layer optimization model to reduce the overall energy consumption. The objective of this work was to provide network-wide optimized TDMA schedules that can increase energy utilization, and reduce end-to-end delay. By using the network-wide flow distribution calculated from the optimization model and the transmission power on every link, the proposed algorithm derives the TDMA schedules and utilize the slot re-use concept to achieve a minimum TDMA frame length. The slot re-use takes place only when the interference is negligible. The model works on a network divided into multiple clusters, each comprising a CH and member nodes that communicate with the CH by single hop. Any suitable clustering scheme selects CHs and gateway nodes that connect neighbouring CHs. After each round of cluster formation, the BS obtains the topology information from the CH and gateway nodes. The BS then calculates the optimized schedule (i.e. the number of slots required on each link and the ID number of the slot in a TDMA frame to be assigned to each required slot) and informs all nodes, after which data communication takes place. The data communication round continues until the energy of a certain percentage of nodes drops below a certain threshold.

Saranya *et al.* [47] pinpointed that routing techniques become inefficient due to the movement of each sensor node in a dynamic WSN. Therefore it is a challenge to transmit data to the BS with less delay in such a dynamic network. Transmitting data by the flooding scheme can minimize the end-to-end delay a however it results in a transmission overhead. This scheme uses the cluster-based routing protocol to broadcast nodes sensed data to all the nearby nodes until it reaches the BS. Here, the sensor nodes with similar mobility pattern are grouped together to form a cluster. Each node maintains a cluster table, which keeps information like the cluster-id, contact probability and time stamp. Two gateway nodes are selected from the cluster member nodes based on the highest contact probability. These gateway nodes act as a bridge between the clusters to transmit the data to the BS so that it minimizes the delay in the network. The proposed scheme shows less end-to-end delay for a dynamic WSN.

2.1.2.4 Overhead Message Aware Clustering Techniques

This section presents the state-of-the-art clustering techniques that exploit the message overhead to form the cluster. Low message complexity is one of the important properties of the self-organization algorithms for WSN because of the constraints of limited bandwidth and energy resources available in these networks. Minimum message transmission of these algorithms means minimum energy consumption and bandwidth utilization. Designing a message-efficient clustering algorithm for a WSN with location unaware sensor nodes poses an additional challenge.

Krishnan *et al.* [48] proposed message-efficient algorithms for improving the clustering efficiency in a WSN. In their method, clustering of a large network begins with initiator or CH nodes that are probabilistically selected. According to them, initiators should be spaced apart both in time and space. If initiator nodes are set too far apart, then it will take too great of a network decomposition time. On the other hand, if several initiators are concurrently active, some initiators will produce clusters of smaller size. The authors proposed a different set of initiators or a CH in different rounds, like LEACH, for load balancing. The network clustering time is logarithmic with the number of nodes in the network, and hence the upper bound of this time has also been derived. They introduced two algorithms: the first algorithm is called *Rapid*, which produces clusters of bounded size. The second algorithm is called *Persistent*, which produces a cluster of the specified bound if possible. The proposed algorithms shows better performance than the commonly used expanding ring algorithm in terms of message complexity. However, the proposed scheme is not energy efficient.

While most efforts discussed so far have focused primarily on an energy-efficient clustering scheme, the attention to achieving energy efficiency and reliability simultaneously for the multi-hop network is quite limited. Many applications in WSNs, including monitoring patients' health, natural or industrial disasters, military surveillance, and so on, require collection of data for sensor nodes without loss. Factors like signal interference and environmental noise deteriorate the wireless link quality, which in turn causes data loss. Data loss also takes place at the CH nodes when they become congested due to handling too much data traffic. Thus, both link quality and congestion can degrade the reliability of the network. Therefore, ensuring reliability at the time of network clustering is essential. It is also crucial to reduce the energy consumption of a WSN. As sensor nodes are equipped with small energy storage, efficient utilization of energy can save precious energy and extend the lifetime of a WSN. Therefore we need to consider both reliability and energy efficiency while developing a cluster technique for a WSN.

2.2 Cluster Number Determination Techniques

Similar to the WSN clustering techniques, the optimal number for a CH determination process can be broadly categorized in two ways: (i) location aware and (ii) location unaware cluster number determination techniques. These are described in the following.

2.2.1 Location Aware Cluster Number Determination Techniques

Xin *et al.* [21] presented a technique for determining the minimum number of CH based on the assumption that each node can obtain its own location information and is able to transmit its data packet to the BS. To find out the optimal number of CHs, they assumed six neighbor nodes (M_1, M_2, M_3, M_4, M_5, and M_6) of a CH node, M_0, and construct a hexagon as is shown in Fig 2.11. The distance between any two nodes is $\sqrt{3}(r_c - \varepsilon)$, $\varepsilon \to 0$, where, r_c is the optimum radius of a cluster. If the distance of any two nodes is longer than $\sqrt{3}r_c$, the sense zone will be uncovered. Fig. 2.11 shows the minimum overlapping area among neighboring clusters. The CH node, M_0 forms a hexagon whose side length is $\sqrt{3}r_c$ and the area of the hexagon is $\sqrt{3}r_c$. The expected number of CHs for the area is calculated as [21],

$$k_{expected} = \lceil \frac{(4\|\|A\|\|)}{3\sqrt{3r_c^2}} \rceil$$

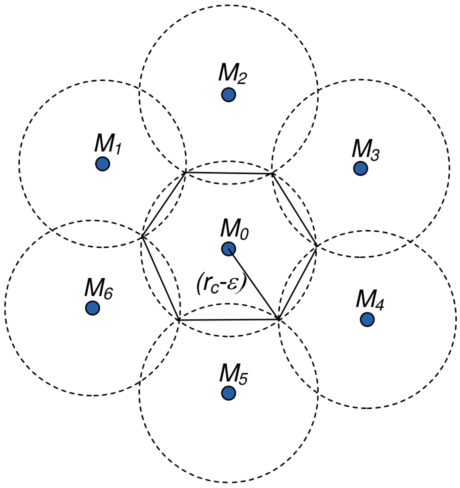

Figure 2.11: Cluster area represented by virtual hexagon.

where, A is the area of sense zone. After determination of the number of CHs in the sense zone, the circular sense zones are divided into many virtual hexagons, to avoid the problem of overlapping nodes.

Wang *et al.* [123] pointed out that current optimal cluster number determination methods are based on each individual protocol layer aspect. However, this number depends on different aspects of the protocol layers [124, 125, 126]. Therefore, they proposed the [123] PHY/MAC/NET cross-layer analytical approach for determining the optimal cluster numbers in a dense sensor network to reduce the energy consumption in the network. The analysis of the cross-layer design incorporates many effects, including log normal shadowing, path loss model, MAC scheduling and multi-hop routing schemes for location aware sensor nodes. Although the optimal cluster number determination and clustering process are closely coupled, as far as we are aware no clustering technique exists in the literature that has considered them together.

2.2.2 Location Unaware Cluster Number Determination Techniques

Determining the optimum cluster number in a WSN cluster analysis is one of the major problems researchers are facing. A number of works [12, 1, 127, 128, 129, 2, 130] have been carried out to determine the optimum number of clusters in the network for location unaware sensor nodes. Although LEACH [12] determines cluster numbers and proposes a complete clustering technique, in the analysis it considers direct communication from all CHs to the BS, which is not energy efficient. A guideline to decide whether a single hop or multi-hop mode of communication will be utilized for sending data from member nodes to their respective CHs has been given in [1]. A cost-based analysis of both the modes and the determination of the required number of CHs has been presented in this paper. In this scheme, sensor nodes alternate between single hop and multi-hop modes periodically to obtain a more uniform load distribution. As presented in the paper (Fig. 2.12), energy expenditure increases with the distance from the CH for a single hop mode, while energy expenditure decreases with the distance from the CH for a multi-hop mode. Whereas the hybrid mode reduces the overall energy cost of the network as compared to a pure single hop or pure multi-hop mode. However, this scheme is sub-optimal as it does not take into account all the possible multi-hop paths. To reduce the energy consumption and to avoid the strict synchro-

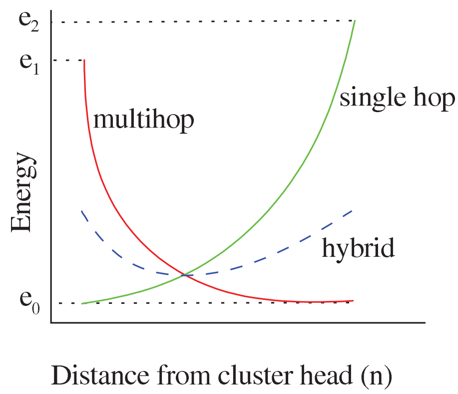

Figure 2.12: Energy consumption in single hop, multi-hop and hybrid communication modes (Source ref [[1]]).

nization requirements of the TDMA, Yang *et al.* [131] applied a sleep-wakeup-based decentralized MAC protocol to the LEACH. They also provided an analytic framework for obtaining the optimal probability of a node becoming a CH node, so that energy consumption in the whole network is minimized. However the analysis suffers from the same unrealistic assumption; that CH nodes directly transmit data to the BS. As a result, the number of optimum CHs determined by this process becomes imperfect and fails to show utmost efficient energy utilization in the simulation results.

Ning *et al.* [128] optimally determined the location of CHs in order to minimize communication power. They considered that each sensor node connects to at least

p CHs for reliability, and each CH can accept at most q connections. Then an optimization problem is formulated to solve the CH deployment problem. They also proposed to use an incremental deployment scheme for the scenario where new sensor nodes or cluster-heads are added to an existing deployment. The proposed incremental deployment approach involves more time and processing complexity, which is not feasible for practical deployment. The clustering approach presented in [129] is capable of producing more stable clusters and can reduce the overhead to maintain the cluster architecture. It is identified that cluster maintenance overheads can be minimized by minimizing the number of generated clusters and the variance of the number of cluster members. Thus, the scheme considers connection duration and CH location as the CH selection criterion and tries to optimize these two objects simultaneously using the Genetic Algorithm.

Bandyopadhyay *et al.* [32] deduced an optimal probability of becoming a CH for each node in a hierarchical clustered WSN. However, in their system energy model, they simply assumed that each node uses 1 unit of energy to transmit 1 unit of data and never considered the energy consumed for receiving the data by the receiver. Thus, the results results obtained in [32] are not directly applicable to other clustering algorithms in practice. The authors also assumed that all nodes transmit at the same power level and hence have the same radio range. However, both intra and inter-cluster transmission radio ranges are usually different. Finally, the communication environment is taken as contention and error free, hence the sensors do not require re-transmission of data. Due to all of these unsuitable assumptions, a determination of optimal CH probability is not so effectual.

There are a number of techniques available in the literature that determine the optimal number of clusters, assuming that n number of nodes are uniformly distributed on a region according to a homogeneous spatial Poisson process of intensity λ and a node becomes a CH with probability p [2, 127]. Li *et al.* [2] identified the above problem [32] and described a method where they obtained the optimal probability of becoming a CH for a node through minimizing energy cost consumed in the system. This method only extends the network lifetime. In Li *et al.*'s cluster analysis, they derived optimal probability for both direct and multi-hop communication between the CH and the BS using the same radio transmission energy model. All communications that take place are assumed to be error free. Therefore, np nodes will become CHs on average. CH and CH member nodes are distributed according to the two independent homogeneous Poisson processes, Π_1 and Π_0. Each member node joins the cluster of the closest CH to form a Voronoi tessellation [132], as shown in Fig. 2.13. At first, energy

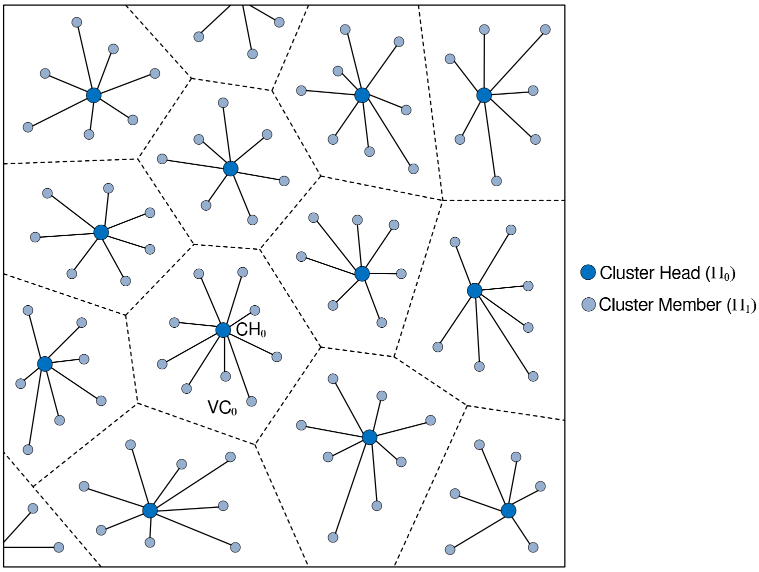

Figure 2.13: Voronoi cells representing clusters.

consumption for the entire network was estimated for direct communication between the CH node and the BS. The optimal CH probability p_{op} is then calculated, for which this total energy is minimized. The same procedure is followed to get the optimal CH probability p_{op} for multi-hop communication between the CH node and the BS. The analytically obtained values of optimal CH probability p_{op} for direct communication and multi-hop communications are listed in Tables Table 2.1 and 2.2. However, the another major limitation of this method is that it used the same energy consumption model (2.4) for both intra and inter-cluster communications.

Simulation was also performed to obtain the optimum CH probability, the results of which aligned with the analytically obtained values.

The optimal clusters are those where member nodes can communicate in one hop to the CH. Therefore, multi-hop intra-cluster communication [34, 130] has not been considered in this thesis.To analyse optimal cluster sizes, uniform node distribution was considered and multiple parameters (e.g. the number of BS, position of the CH, in-network processing) were used in the research to characterize the WSN. Again, the

Table 2.1: Optimal values of cluster probability for single-hop WSN (data is extracted from [2]).

Sensing Area	**Total Nodes (n)**	**Node Density** (σ)	**CH Probability** (p_{op})
From (0,0) to (100,100)	500	0.05	0.0618
	1000	0.10	0.0437
	1500	0.15	0.0357
	2000	0.20	0.0309

Table 2.2: Optimal values of cluster probability for multi-hop WSN (data is extracted from [2]).

Sensing Area	**Total Nodes (n)**	**Node Density** (σ)	**CH Probability** (p_{op})
From (0,0) to (1000,1000)	500	0.0005	0.0603
	1000	0.0010	0.0456
	1500	0.0015	0.0385
	2000	0.0020	0.0340

research has not answered the question of how to find and build this clustering with little overhead.

All of the above works have been carried out for a WSN with uniform sensor node distribution and have only tried to minimize the energy consumption of the network. While most of the techniques looked at the energy minimization issue, all of them ignored data reliability and other factors (e.g. message overhead) when determining the optimal cluster number. The optimal cluster number for the network may vary depending on the deployment context and the type of applications. However, existing optimization techniques calculate the number of CHs prior to the deployment of a WSN. This creates a gap between the number and their clustering process during deployment. This has promoted the introduction of a new research technique for the determination of the optimum cluster number and application of this number in the clustering algorithm that should be performed jointly to achieve energy efficiency and reliability of the network. This thesis will address the issues and challenges related to location unaware clustering techniques in the subsequent chapters.

2.3 Summary

Designing WSN cluster-based routing protocols should consider their feasibility for deployment and should be application oriented. A major portion of sensor research has assumed that nodes are equipped with a GPS receiver, which is also not suitable for WSN applications with a large number of nodes, as they involve a huge deployment cost. Most of the existing research work has addressed the issue of energy constraint and has tried to extend the network lifetime.

We have investigated both location aware and unaware clustering protocols and presented these in detail in Section 2.1. All of the existing WSN clustering protocols have their advantages and drawbacks. Although some of these techniques address lifetime and scalability goals, they suffer from excessive data loss or messaging overhead. A few of them have concentrated on achieving reliability with a sacrifice of the network lifetime. Some others have shown better energy utilization in the network, however they have incurred a high messaging overhead.

The backup clustering method has been shown to be very important in enhancing the reliability of a WSN and, therefore, all the existing location aware and unaware backup or proxy clustering techniques are described in Section 2.1.1.2 and Section 2.1.2.2. The performance of these protocols is limited and depends on an intuitively selected threshold to switch the current CH role to a backup/proxy CH node. Achieving reliability and energy energy efficiency simultaneously is identified as the basic requirements of any practical WSN application. Therefore, any clustering and backup clustering protocol needs to address these two basic parameters and only then can a cluster-based routing protocol be beneficial in real life applications.

A survey of the optimal cluster number determination process has been articulated in Section 2.2. Most of the clustering techniques require an a priori cluster number. Each of these research efforts have identified the determination of an optimal cluster number as the key challenge and have calculated the suitable value so that it minimizes the energy consumption in the network. Most of them assumed a WSN with uniform node distribution for determining the cluster number. In addition, none of these approaches has considered the issue of reliable data transfer while calculating the optimal cluster number.

This chapter has presented an overview of the existing location aware and location unaware clustering, backup clustering and cluster number determination techniques. Generally, sensors are very cheap and tiny in size. A location aware sensor node, which is embedded with a GPS unit, is both costly and larger in size. As typical sensor networks require a large number of sensor nodes, this produces a huge deployment cost. In addition to the cost, as sensors are usually deployed in hazardous or inaccessible places, determining sensor location using either a method or a GPS is not always possible. Since these strategies are developed mainly by exploiting the location information in order to handle the signal fading affect efficiently, they need to know the position and characteristics of environmental obstacles. On the other hand, the deployment cost of a location unaware WSN is very low. As the proximity of the location is determined based on the receiving signal strength. These inherently handles the signal fading effect but are naturally unreliable compared with their location aware counterparts. Therefore, clustering protocols for location aware sensor nodes need to consider the nodes' deployment strategy. On the other hand, in the context of a WSN deployed in a real world environment for location unaware clustering, data reliability without sacrificing the network lifetime is an important issue. Often data loss takes place due to signal interference, environmental noise and sudden breakdown of a CH, which are already highlighted in Section 1.3. Therefore, another important challenge is to design a reliable clustering protocol for a location unaware WSN. To address this issue, the next chapter will introduce a backup clustering technique to improve reliability as well as the network lifetime.

Chapter 3

Reliable and Energy Efficient Backup Clustering Technique

Cluster-based routing protocol for WSNs needs to be reliable. To improve reliability it is of paramount importance to reduce the likelihood of sudden breakdown of a CH. As alluded to previously (Section 1.3, Section 2.1.2), a backup clustering technique could be a pertinent solution for this issue. However, the only backup clustering technique available in the literature increases reliability by sacrificing the network's lifetime. In this chapter we address the problem of increasing reliability and network lifetime simultaneously. We introduce a backup clustering technique that considers the nodes' remaining energy, switching energy and average reachable energy. Using average reachable energy forces the process to select a backup cluster head (BCH) in close proximity to its cluster center. This method minimizes the energy consumption of a cluster. Our proposed scheme eliminates the need for a intuitively defined threshold that is required for selecting and switching a BCH. This also improves reliability and the network lifetime simultaneously and exhibits superiority over the available and contemporary technique presented in [55].

To begin the account of this work we present a brief overview of the research problem and its background (Section 3.1). We then elaborate on the models for sensor network energy consumption (Section 3.2) and solar energy harvesting (Section 3.3). Next we describe the operation of the proposed backup clustering protocol, the BCH selection mechanism, its switching method and computational complexity (Section 3.4). Finally, we present the simulation environment used for network performance evaluation and the corresponding simulation results (Section 3.5). At the end, we conclude by summarizing the chapter (Section 3.6).

3.1 Problem Statement

The major overhead of clustering-based sensor networks occurs in the re-clustering process. Let T_C be the re-clustering time of the whole network and T_N be the network operation time as illustrated in Fig. 3.1. The lifetime of a sensor network is $w(T_C+T_N)$, where w is the number of re-clustering process runs until the first node die. In the entire lifetime of a network, the re-clustering process spends a total time of wT_C. This time can be reduced by reducing the frequency of re-clustering (w). Therefore it is necessary to optimally select a set of BCHs for a particular cluster and switch them with the current CH according to their optimum switching time, so that both reliability and network lifetime increases simultaneously. For this, the selected BCHs need to be ranked for a particular cluster so that they can take over the job of the relevant current CH sequentially. This will increase the effective network operation time by reducing the clustering overhead. In addition to energy efficiency, reliability is also a major issue, which is affected mainly by the energy depletion of a CH and the re-clustering process time wT_C. If a node continues in its role as a CH for a long time, it will eventually lose its precious energy faster than its member nodes. In a cluster-based multi-hop WSN, CHs play roles such as data sensing, aggregating and routing. Malfunctioning of some CHs due to power failure can significantly reduce reliability and the network lifetime. Therefore, a significant question of this research is: *how to reduce the re-clustering overhead to increase both reliability and lifetime simultaneously?*

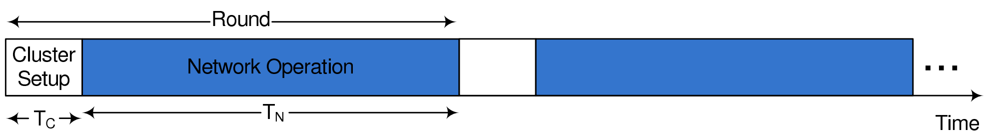

Figure 3.1: The network operation rounds.

3.2 Energy Consumption model of a WSN Cluster

The radio energy dissipation model is presented in the LEACH [12]. For l-bit message transmission over a distance d, we follow the same energy model as defined in (2.4), (2.5) and (2.6). Data transmission during the intra-cluster communication takes place in shorter distances and hence, this communication is dependent on the free space

ε_{fs} channel model [63]. On the other hand, inter-cluster communication necessarily involves a transmission over a large distance, as the distance between two CHs or between CH and the BS ($d_{CH,CH/BS}$), is larger than d_0. Therefore, data transmission is dependent on multi-path fading ε_{mp} channel models, as shown in (2.5). According to the energy model [12], the energy consumed by a CH can be calculated as follows:

$$\begin{aligned} E_{CH} &= E(Data\ sensing) + E(Data\ receiving) \\ &+ E(Data\ aggregation) + E(Data\ Transmissionto\ CH/BS) \end{aligned} \tag{3.1}$$

The value of E_{CH} changes with time and therefore, E_{CH} is updated over that time.

3.3 Solar Energy Harvesting Model

As the world is moving further towards wireless technology, the need for energy to operate wireless devices such as smart phone, laptop, wireless sensor node, etc, is increasing rapidly. Batteries provide the main source of uninterrupted power for all these wireless devices. Disposing of a battery can cause great harm to the environment. The increasing demand for batteries to power wireless devices drives manufacturers to produce more and more batteries; this in turn uses energy, which contributes to global warming. Recently, the scientific research community as a whole has admitted that the biggest challenge to the world at this time is global warming [133].

The seamless operation of wireless sensor nodes for extended periods of time depends on replenishing their energy regularly. While conventional energy sources have proved inefficient, costly and hazardous to the environment, it is time to explore renewable energy sources that can effectively counter these problems. While extending the lifetime of the WSN has been a key research area for scientists for a long time, in recent years, scientists are also putting effort into harvesting renewable energy from the surrounding environment and storing the energy in a node.

Table 3.1 shows several potential energy harvesting modalities [134]. Although a wide variety of power harvesting modalities are available, of these solar energy harvesting through photo-voltaic (PV) conversion gives maximum power density, attracting more attention from researchers as a potential power for wireless sensor node. For example, Texas Instruments developed the eZ430-RF2500-SEH solar energy harvesting

Table 3.1: Power Densities of Harvesting Technologies

Harvesting technology	**Power density**
Solar cells (outdoors at noon)	$15mW/cm^2$
Piezoelectric (shoe inserts)	$330\mu W/cm^3$
Vibration (small microwave oven)	$116\mu W/cm^3$
Thermoelectric (10^oC gradient)	$40\mu W/cm^3$
Acoustic noise (100dB)	$960nW/cm^3$

development kit, as shown in Fig. 3.2. This module includes a high-efficiency solar ($2.25'' \times 2.25''$) panel optimized for operating indoors under low-intensity fluorescent lights. It also manages and stores additional energy in a pair of thin-film rechargeable EnerChips.

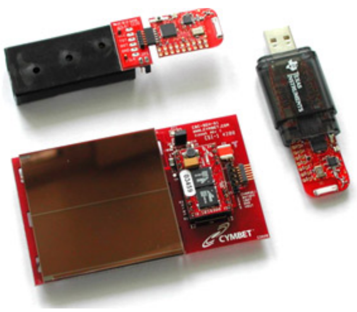

Figure 3.2: Solar energy harvesting sensor node developed by Texas Instruments

Utilizing solar power for energy generation involves several complexities, such as the property of the solar cell, battery capacity, sunlight requirement, power management technique and application behavior. It is therefore necessary to thoroughly understand and analyze these factors in order to maximize energy utilization from a solar energy module. Although it is agreed that harvesting solar energy is a promising option, it poses a challenge for researchers in terms of how to effectively produce, store and efficiently use this energy for sensor nodes.

Fig. 3.3 shows an overall structural model of a solar powered sensor node. Each of the structural units of the wireless sensor node is discussed as follows:

1. *Processing unit:* This consists of a micro-controller and memory. It is responsi-

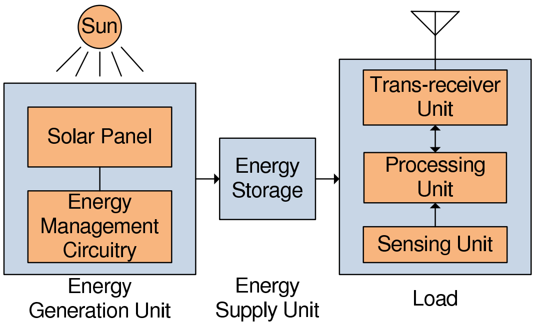

Figure 3.3: Structural flowchart of a solar powered WSN

ble for controlling the sensor, processing the sensing data and carrying out the communication protocol. The processing unit has a large impact on the energy consumption of the node. An example of a typical micro-controller used in a sensor node is the $Texas\ Instruments\ MSP430$. This is a 16bit CPU with 16-bit registers and ultralow-power micro-controller, which consumes $280\mu A$ at 1 MHz in Active mode, $1.6\mu A$ in standby mode, and $0.1\mu A$ in Off mode.

2. *Transreceiver unit:* This communication subsystem includes a baseband signal process and radio sections. Each node consumes energy for receiving and transmitting data wirelessly at different rates. For example, the CC2420 is a low-cost, single-chip, IEEE 802.15.4 compliant RF transceiver for robust wireless communication in the 2.4 GHz unlicensed ISM band. It has low current consumption (RX: 18.8 mA, TX: 17.4 mA).

3. *Sensing unit:* A range of natural phenomenon, such as light, heat, sound, vibration, etc. is sensed and then data is generated in digital mode by the unit. For example, DS18B20 is a digital thermometer which provides 9-bit to 12-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points.

4. *Energy supply unit:* This subsystem includes an energy generation module, a energy management module, and an energy storage module.

Energy storage technologies: Two available energy storage technology options are batteries and supercapacitors. Supercapacitors have much higher power density than conventional capacitors and all types of batteries. They do not contain any chemicals and are safe from explosion, fire and smoke. Another major advantage of supercapacitors over batteries is that they have virtually unlimited life cycle and simple charging methods. On the contrary, these capacitors has the property of self-discharge, or internal leakage current, which is higher compared to the conventional batteries. Four types of rechargeable batteries are commonly used: Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium based (Li+), and Sealed Lead Acid (SLA).

Characteristics of a solar cell: A solar panel behaves as a voltage limited current source (as opposed to a battery which is a voltage source) [135]. Maximum power can be extracted from the panel at an optimal operating point. Source current increases or decreases as the amount of incident solar radiation increases or decreases, while voltage remains almost constant. A solar panel cannot be used directly as an energy source due to its current source-like behavior. Thus, it is necessary to store this harvested energy in a battery to provide a stable voltage to the system.

3.4 Proposed Backup Clustering Protocol

3.4.1 Network Model

Establishing a wireless sensor network can be considered wherever sensors are randomly distributed over a two-dimensional area with a BS placed at one corner. Their primary task is to monitor events and report data periodically. The location information of the nodes is unknown to each other, as they are not equipped with GPS or positioning algorithms. Nodes are capable of communicating with a fixed number of transmission power levels. An example of such sensor nodes are Berkeley Motes [136]. Links are considered bidirectional and symmetric; i.e. two nodes can communicate using the same transmission power level. Nodes are assumed stationary or to be have limited mobility. The proposed backup clustering scheme could be used in any suitable cluster-based routing protocol for wireless sensor networks.

3.4.2 Protocol Operation

In this section we propose a new backup clustering scheme. This scheme takes into consideration the residual energy (E_{RE}), average reachable energy (ARE), switching energy (E_{sw}), sensing energy (E_S), energy for data aggregation (E_{da}), and energy spent to communicate with the other CHs (inter-cluster communication) or the BS. Now it is considered that variable power levels are allowed for intra-cluster communication. $MinEn_t$ is the minimum energy required by t^{th} member node ($1 \leq t \leq C_i$) to transmit the sensed data to CH_i, where, C_i is the number of member nodes within the cluster, CH_i. Then, ARE is defined as the average minimum energy required by all member nodes within the cluster range to reach the i^{th} cluster head, CH_i, i.e.,

$$ARE_i = \frac{\sum_{t=1}^{C_i} MinEn_t}{C_i}$$

The ARE of a CH node represents the expected minimum intra-cluster communication energy consumption if that node is selected as a CH, which gives a proper estimate of the communication cost. Thus, ARE can play an effective role in the BCH selection process, which minimizes the intra-cluster communication cost. A CH selects a set of BCHs just after the formation of that cluster. To do this, the CH uses E_{sw}, E_{RE} and ARE of each member node, which are obtained during their time of joining. The current CH also calculates the optimal switching time based on E_{RE}, E_{sw}, E_{non-CH} and energy consumed by a CH (E_{CH}), which includes energy for data aggregation, transmission to the BS, sensing and all other energy required for intra and inter-cluster communication. Then it initiates the switching operation by sending a single update message. The sequence of protocol operations can be described as follows:

1. The current CH optimally selects and ranks a set of BCHs from all member nodes and calculates their optimal switching time. Since the E_{CH} changes over the time, the switching time is updated in each data collection cycle.

2. At its switching time, the current CH chooses the first BCH from its ranked set of BCHs and broadcasts the BCH information by a single update message.

3. The new CH takes over the role of the current CH and forwards its aggregated data to the same node, as performed by the previous CH. It also follows the same TDMA schedule as the previous CH, except it replaces itself in the previous CH node's position. The BCH switching and handing over the CH role is illustrated in Fig. 3.4. Here, node 2 hands over the CH role to node 4 and node 4 forwards packets to the same forwarding node 1.

4. All member nodes of that cluster update their current CH information on receipt of the update message.

5. All the member nodes of that cluster, including the CH that has been replaced, join the new CH as its member nodes.

6. Other CHs in the adjacent clusters update their multi-hop routing table on receipt of this update message.

7. A newly selected BCH is removed from the ranked BCH set and the CH switching process continues until the next round of re-clustering.

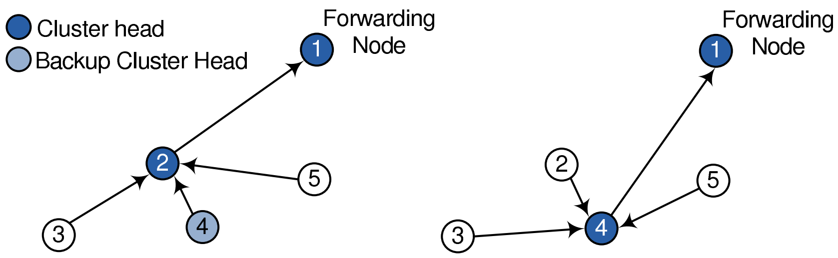

Figure 3.4: Switching to backup cluster head

In order to improve energy efficiency, even though the BCH is selected considering its E_{RE}, E_{sw} and ARE, the position of the selected BCH may require some of its own and neighbouring clusters' member nodes to be redistributed amongst them, as is illustrated in Fig. 3.5 and Fig. 3.6. Here, A and B are two neighbouring clusters, where the BCH switching is taking place in cluster A. The current and selected BCH are represented by circles filled with black and gray colors respectively. After switching to BCH in cluster A, two member nodes of cluster B, indicated by m_1 and m_2 as shown in Fig. 3.6, are required to rejoin with cluster A. Similarly, the two member nodes of cluster A represented by m_3 and m_4 also need to be redistributed to their nearest clusters.

It is noteworthy that very few control messages are required to perform the above switching process. In the backup clustering process, the current CH sends a message to the new BCH node and, after receiving the message, the BCH node sends an acknowledgement message to the current BCH. Then the new BCH broadcasts the information regarding becoming a CH within its one hop neighbours. Upon receiving

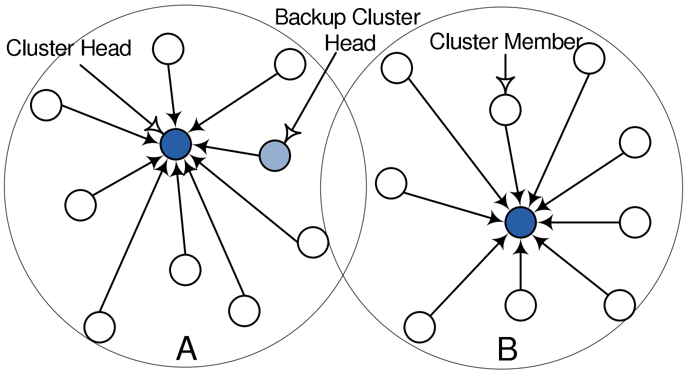

Figure 3.5: Illustration of (before) switching to BCH

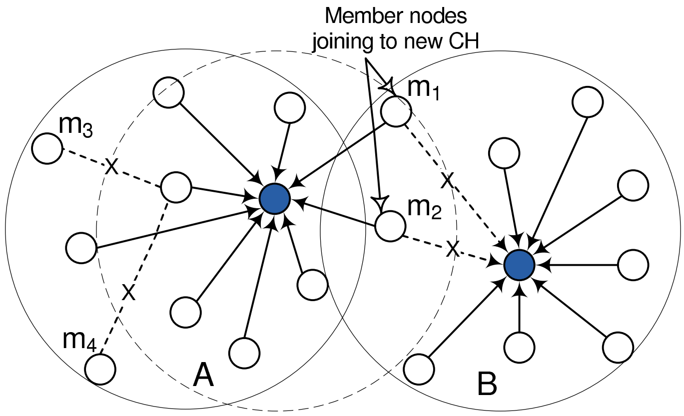

Figure 3.6: Illustration of (after) switching to BCH

this message, the respective member nodes send a joining message to the newly selected BCH as a cluster member. Since the broadcasted information is limited to only one hop neighbours, it does not affect the scalability of the network. The number of control messages required for BCH switching is approximately one for each member node, whereas HEED re-clustering requires at least six iterations by each of the nodes. Therefore it is expected that the overhead for BCH is considerably less than that of HEED re-clustering.

It is unlikely that all clusters in the network will start the CH switching operation at the same time. Rather, only the CH calculate and triggers the switching operation when its energy reaches a certain level. Although the CH switching operation takes place in one cluster, regular network operations in the other clusters remain uninterrupted. The switching operation takes a relatively short time compared to the time needed for re-clustering, as illustrated in Fig. 3.7. This eventually reduces the number of

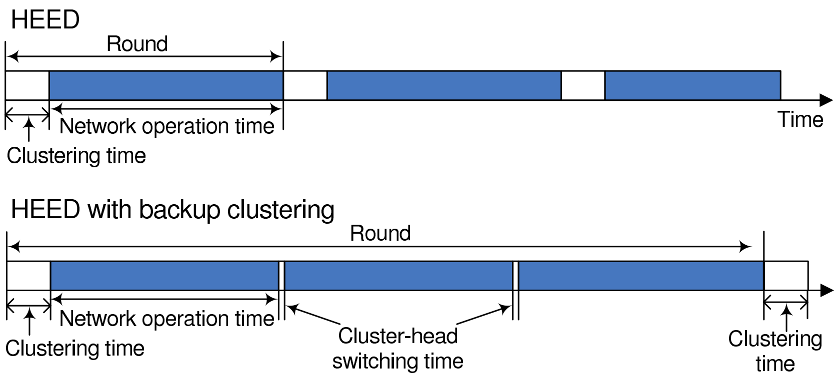

Figure 3.7: Time line of HEED with backup clustering

re-clusterings and hence improves both network lifetime and reliability.

3.4.3 Backup Cluster Head Selection

The objective is to select a set of BCHs by minimizing the overall energy spent in a cluster. Therefore, the optimal selection of a BCH can be defined as follows:

$$
\begin{aligned}
i \;&=\; \arg_{1 \leq i \leq u} \min\{P_i E_{sw} + ARE_i\} \\
&\quad where, \;\; P_i = \lfloor \frac{E_{max} - E_{RE_i}}{E_{sw}} \rfloor + 1
\end{aligned}
\tag{3.2}
$$

where i represents the ID of a node to be selected as a BCH, u denotes the number of nodes within a cluster range. E_{max} is the maximum energy of the sensor node and E_{RE_i} is the residual energy of i^{th} member node in a cluster. In the selection process of a BCH, since a small value of E_{RE_i} will require more frequent switching, a parameter is needed that (e.g., P_i) can represent the frequency of switching a BCH if it were selected with respect to E_{max}. In this case, P_i will be less for the node with higher remaining energy; consequently, this places the emphasis on the nodes with higher remaining energy in the selection process. Again, a node with low E_{RE_i} will yield a high P_i value, which eventually places the node in the lower ranks of the BCH selection list. In addition to this, ARE_i in (3.2) will impose an additional condition so that a node in close proximity to a cluster center has a higher chance of being selected as BCH. This eventually will minimize the energy required for intra-cluster communication. Thus, (3.2) ensures selection of a node as a new CH with minimum ARE and maximum residual energy within a particular cluster. The pseudo-code for BCH selection is given in Algorithm 3.1.

Algorithm 3.1 Select BCH

Initialization:
$S1 \leftarrow \{v : v\ is\ a\ member\ node\ of\ a\ cluster\}$
Broadcast E_{RE} to $S1$
Compute ARE and broadcast to $S1$
$E_{sw} \leftarrow$ Switching energy
$m \leftarrow$ number of BCH
$M \leftarrow$ set of estimated energies for the member nodes of a cluster
procedure SelectBCH(E_{RE}, ARE, E_{sw}, m)
    $maxE_{RE} \leftarrow max_{i\epsilon S}(E_{RE_i})$
    for all $i \in S1$ **do**
        $P_i \leftarrow \frac{maxE_{RE} - E_{RE_i}}{E_{sw}}$
        $M_i \leftarrow ARE_i + P_i E_{sw}$
    end for
    Sort M in ascending order
    Select first m nodes from M
end procedure

3.4.4 Calculation of Threshold Energy and Time for Switching

Switching energy represents the energy required to bring a BCH to the role of a current CH, such as sending a control message to the selected BCH, receiving its control message and broadcasting BCH information to its member and other relevant CH nodes. Since frequent switching consumes more energy, it is necessary to calculate an optimum time to switch from a CH to its respective BCH.

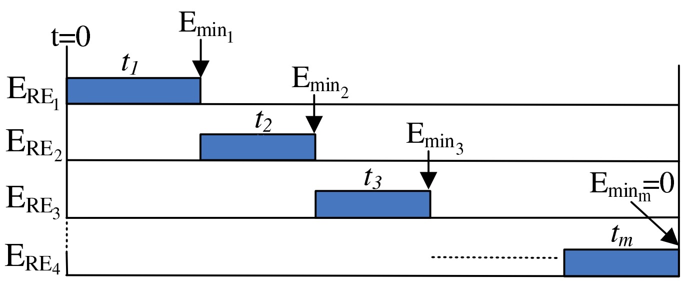

Figure 3.8: Time line of backup cluster head switching

Let t_{CH_i} be the optimum switching time for CH_i and t_{non-CH_i} be the time for a node to act as a member node. E_{CH_i} is the energy consumed by i^{th} node as a CH per unit time. Here, E_{non-CH_j} is the energy required per unit time by a member node of j^{th} cluster. Suppose that, from all member nodes in a cluster, m number of nodes are selected to perform as BCH. Then, as shown in Fig. 3.8, the cluster life-time will be

$$t_{CH} = t_{CH_1} + t_{CH_2} + t_{CH_3} + \ldots + t_{CH_m} = \sum_{i=1}^{m} t_{CH_i} \tag{3.3}$$

From Fig. 3.8, t_{CH_i} can be defined as,

$$t_{CH_i} = \frac{E_{RE_i}(t^{'}) - E_{min_i}(t) - E_{sw}}{E_{CH_i}(t)} \tag{3.4}$$

where, $t^{'} = \sum_{k=0}^{i-1} t_k$, $t = \sum_{k=1}^{i} t_k$ and $E_{min_i}(t) = \sum_{j=i+1}^{m} t_{non-CH_j} \times E_{non-CH_j}$. Therefore, the objective is to maximize t_{CH} so that the cluster life-time is maximized. The optimal selection of a BCH switching time can be defined as follows:

$$\begin{aligned} \max \quad & t_{CH} \\ \textit{subject to } & E_{min_m} = 0. \end{aligned} \tag{3.5}$$

Here, E_{CH_i} changes with time, as this energy is dependent on data collection, aggregation and transmission. It is considered that the energy spending rate of a CH is as it is calculated at the beginning of its operation as a CH node. E_{CH_i}, and thereby switching time, are re-estimated by a CH node regularly in each data collection interval from the member nodes.

To find the optimal switching time t_{CH_i} for CH_i using (3.5) requires the value of E_{min_i} except E_{min_m}, which is equal to zero, is a NP hard problem. Therefore an analytical solution for (3.5) does not exist; consequently, it has been solved numerically. The pseudo-code of this numerical solution is presented in Algorithm 3.2. In Step 9 of Algorithm 3.2, t_{CH_i} is initialized with the proportionate value of its remaining energy. In order to ensure that $E_{min_m} = 0$, the remaining time of CH_m, after playing the role as a CH node, should be proportionately distributed so that Algorithm 3.2 converges within a few iterations. The increment factor is calculated considering the remaining time of CH_m in Step 16. Using this, the value of t_{CH_i} and $t_{non\_CH_i}$ have been updated in Step 18 and 19. The algorithm iterates until it converges, which is dictated by the condition articulated in Step 22.

3.4.5 Computational Complexity Analysis

Lemma 1: BCH selection algorithm (Algorithm 3.1) has a processing time complexity of $O(klogk)$ for a cluster of k number of member nodes.

Algorithm 3.2 Calculate BCH Switching Time

Initialization:
$S2 \leftarrow$ SelectBCH(E_{RE}, ARE, E_{sw}, m) of Algorithm 3.1
$E_{non-CH} \leftarrow$ Energy required by non-CH nodes per unit time
Compute E_{CH}
procedure SwitchingTime(E_{RE}, E_{CH}, E_{non-CH}, $S2$)
  $total\_t_{CH} \leftarrow 0$
  $maxE_{RE} \leftarrow max_{i \epsilon S2}(E_{RE_i})$
  for all $i \in S2$ **do**
    $t_{CH_i} \leftarrow \frac{E_{RE_i}}{maxE_{RE} \times m}$
    $t_{non\_CH_i} \leftarrow (E_{RE_i} - t_{CH_i} \times E_{CH_i}) / E_{non-CH_i}$
    $total\_t_{CH} \leftarrow total\_t_{CH} + t_{CH_i}$
  end for
  repeat
    $prev\_total\_t_{CH} \leftarrow total\_t_{CH}$
    $total\_t_{CH} \leftarrow 0$
    $\Delta T \leftarrow \frac{(t_{non\_CH} \; of \; last \; node - total\_t_{CH} \; except \; last \; node)}{(maxE_{RE} \times m^2)}$
    for all $i \in S2$ **do**
      $t_{CH_i} \leftarrow t_{CH_i} + \frac{E_{RE_i}}{maxE_{RE}} \times \frac{E_{CH_i}}{E_{CH_i} + E_{non-CH_i}} \times \Delta T$
      $t_{non\_CH_i} \leftarrow (E_{RE_i} - t_{CH_i} \times E_{CH_i}) / E_{non-CH_i}$
      $total\_t_{CH} \leftarrow total\_t_{CH} + t_{CH_i}$
    end for
  until $(total\_t_{CH} - prev\_total\_t_{CH}) > \xi$
end procedure

Proof: For BCH Selection, using Algorithm 3.1, the protocol takes a processing time at most $O(k)$ to compute the cost based on E_{RE} and ARE. CH switching also takes a processing time of $O(k)$. However, sorting of k values using quick sort [137] requires $O(klogk)$. As an iteration has an $O(1)$ time complexity, the overall computational complexity of Algorithm 3.1 is $O(klogk)$.

Theory 1: The BCH algorithm has $O(k)$ less message exchange complexity during switching when compared to HEED for re-clustering in the network.

Proof: BCH in switching has a message exchange complexity of $O(1)$ per node; i.e. $O(k)$ in the network. According to [14], the number of messages exchanged in the network is upper-bound by $n_{iter} \times n$, i.e., $O(n)$, where n is the number of nodes in the network. As $k < n$, the message exchange complexity of the BCH algorithm is very low compared to the HEED clustering. □

Lemma 2: The newly selected BCH in area A can communicate with the neigh-

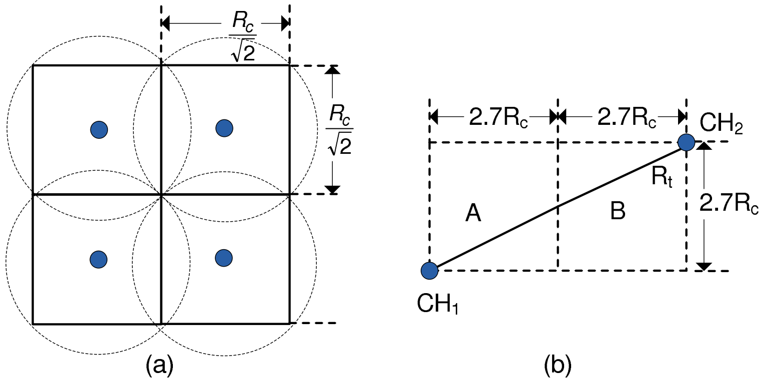

Figure 3.9: Transmission range for CHs' connectivity

bouring CH in area B, where the size of the area is $(2 + 1/\sqrt{2})R_c \times (2 + 1/\sqrt{2})R_c$, if $R_t \geq 6R_c$.

Proof: A similar theorem was proved in [14]. However, this lemma is proved by contradiction in the backup cluster-head scenario. According to Fig. 3.9, one cluster head (CH_1) is in the bottom left corner of area A and another cluster head (CH_2) is in the top right corner of area B of size $(2+1/\sqrt{2})R_c \times (2+1/\sqrt{2})R_c$. Using Euclidean geometry, the distance between CH_1 *and* $CH_2 \approx 6R_c$. If a node is selected as BCH, which sets the transmission range R_t for CH_2 to reach the new BCH CH_1 as more than $6R_c$, then the new BCH must fall outside the cluster area A, which is not possible.

3.5 Simulations

3.5.1 Simulation Setup

The simulations are designed to study the performance of a network lifetime, its reliability and the message overhead incurred by the entire sensor networks. An extensive simulation has been carried out using the popular HEED [14] clustering protocol, which is implemented using TOSSIM (A discrete event simulator for TinyOS). HEED considers the residual energy of the node and a secondary parameter, such as the node's proximity to its neighbours or the node degree for CH selection. It does not require special node capabilities such as location-awareness.

The initial energy of a sensor node is considered to be $0.5J$. It is assumed that the links are symmetrical and there are no noise or environmental effects on the signal communication. Energy spending due to data aggregation and multi-hop data forwarding by a CH has been considered to achieve more realistic and practical results. The HEED clustering protocol and the backup clustering scheme introduced in [55], called BCH_Hashmi over HEED, is simulated. The implementation of the proposed backup clustering scheme is carried out on top of HEED to compare the network lifetime and reliability of the proposed scheme with HEED and BCH_Hashmi. For a fair comparison, the network topologies, node distribution, node-energy distribution, channel propagation model and other simulation parameters have been kept identical across all protocols. The number of nodes to be deployed in a WSN totally depends on the type of application. It can be tens or hundreds of nodes based on a small, medium or large size WSN. For testing the effectiveness of the clustering or backup clustering algorithm, it seems to be reasonable to simulate a WSN with several hundred nodes. Therefore, the simulation of our proposed backup clustering technique has been conducted using 200 and 300 sensor nodes. Each sensor node is uniformly distributed in a $200m \times 200m$ area. A node is considered "dead" if it has lost 99% of its initial energy. As with [14], the simulation parameters are listed in Table 3.2.

Table 3.2: Simulation Parameters

Description	**Parameter**	**Value**
Initial energy	E_i	0.5J
Electronic circuitry energy	e_{elec}	50nJ/bit
Multi-path co-efficient	ε_{fs}	10 $pJ/bit/m^2$
Free space co-efficient	ε_{mp}	0.0013 $pJ/bit/m^4$
Cluster Radius (range)	r	25m
Data aggregation energy	E_{da}	5 nJ/bit/signal
Switching Energy	E_{sw}	50 nJ/bit
Data packet size	p_{pkt}	30 bytes
Broadcast packet size	p_b	25 bytes

3.5.2 Performance Evaluation

In this section, a performance evaluation of the proposed backup clustering scheme has been carried out using simulations. As a performance metric, firstly we compare the network lifetime considering both the first and last node death of the proposed single (Single_BCH) and multiple (Multiple_BCH) backup clustering schemes with HEED and BCH_Hashmi. Secondly, we compare the Data Loss Ratio (DLR) for the proposed Single_BCH and Multiple_BCH schemes with HEED and BCH_Hashmi. DLR is the ratio of the difference of total data sent by the sensor nodes and received at the base station to the total data sent by the sensor nodes, as given below:

$$DLR = \frac{TotaDataSent - TotalDataReceived}{TotaDataSent} \tag{3.6}$$

Finally, a comparison with respect to the message overhead is also provided. In order to check which algorithm promotes a sustainable environment, performance analysis has been presented both with and without using sensor nodes equipped with a solar cell.

3.5.2.1 Without Solar Energy

Energy efficiency measure: Simulation results in Fig. 3.10 and Fig. 3.11 show the lifetimes of WSN networks with $n = 200$ and 300 nodes respectively. According to Fig. 3.10 and Fig. 3.11, an overall lifetime gain is achieved by the proposed single_BCH and multiple_BCH schemes over both HEED and BCH_Hashmi protocols for WSNs with 200 and 300 sensor nodes.

For a WSN with 200 nodes, as illustrated in Fig. 3.10, the single_BCH has achieved a 37% and 10% increase in network lifetime over HEED for the first and last node death respectively, while the results are a 42% and 18% increase for the multiple_BCH scheme. Here, compared to the BCH_Hashmi protocol, the lifetime increase is 48% and 13% for the first and last node death respectively for the single_BCH scheme and 52% and 21% for the first and last node of the multiple_BCH scheme. Fig. 3.10 also shows that BCH_Hashmi decreases the lifetime of HEED. This is for two reasons: BCH_Hashmi assumes (i) the selection of BCH is based on the remaining energy only and (ii) the switching to the BCH is based on a threshold. The experimental results, as presented in Fig. 3.11, also reflect the increased energy utilization. According to Fig. 3.11, WSN

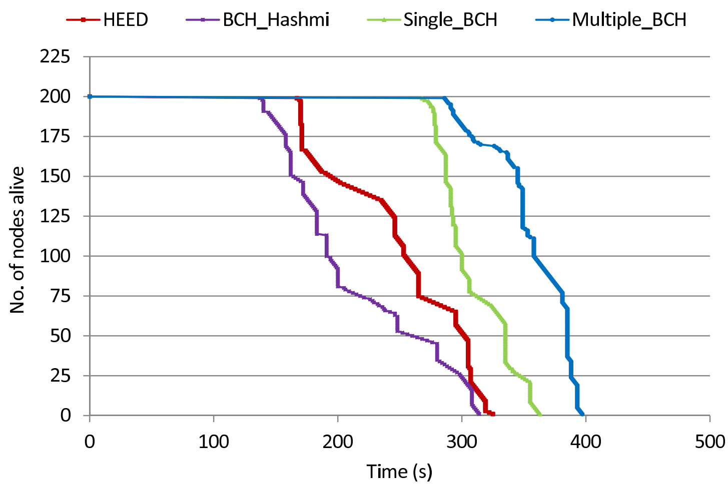

Figure 3.10: Network lifetime using HEED vs backup clustering schemes for WSN with 200 nodes.

with 300 nodes has gained a 34% and 18% increase in lifetime over HEED for the first and last node respectively for the single_BCH scheme; the lifetime gain is 41% and 22% for the multiple_BCH scheme. Moreover, the single_BCH scheme for the WSN with 300 nodes has achieved a 43% and 23% increase in network lifetime over the BCH_Hashmi protocol for the first and last node death respectively; the multiple_BCH scheme has attained a 48% and 26% increase in network lifetime for the first and last node death respectively.

Enhancement in lifetime for both the single_BCH and multiple_BCH has been achieved due to the efficient consumption of energy by the BCH and member nodes where the BCH node selection and switching process is done efficiently. Furthermore, the proposed scheme tends to select a BCH close to the center of a cluster, which reduces the energy consumption of the BCH node and provides better safeguard for the BCH against sudden breakdown. Almost all of the present day applications demand an extended lifetime of the sensor network. Therefore it is necessary to enhance the energy utilization of the network by suitably employing the clustering scheme.

Reliability measure: To obtain the reliability estimation, the DLR is calculated based on (3.6) for WSNs with 200 and 300 sensor nodes. Simulation results are plotted in Fig. 3.12 and Fig. 3.13, which incorporate HEED, BCH_Hashmi and the proposed single_BCH and multiple_BCH protocols.

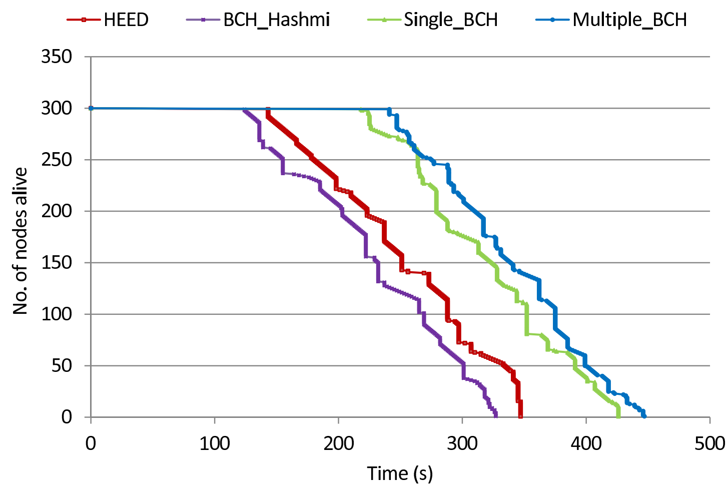

Figure 3.11: Network lifetime using HEED vs backup clustering schemes for WSN with 300 nodes.

The DLR readings for the WSN with 200 nodes are shown in Fig. 3.12, where both single_BCH and multiple_BCH schemes have achieved significant gain compared to the HEED protocol. For the single_BCH and multiple_BCH schemes, the average drop of the DLR is 67% and 76%, respectively, when compared to HEED. When the reliability of the proposed protocol is compared with BCH_Hashmi, the average DLR drops are 24% and 41% for single_BCH and multiple_BCH respectively. On the other hand, the DLR readings for the WSN with 300 nodes, as shown in Fig. 3.13, shows a substantial improvement for both single_BCH and multiple_BCH when compared with HEED. The reliability for the single_BCH protocol produces comparable results to the BCH_Hashmi protocol; for multiple_BCH, a 10% improvement is achieved on average over BCH_Hashmi for the whole of the network operation time.

The results shown in the Fig. 3.12 and Fig. 3.13 affirm that data reliability for both the single_BCH and multiple_BCH techniques of the proposed scheme are much higher than that of HEED and BCH_Hashmi. The reasons a reduced data loss for the proposed schemes is achieved are noteworthy. Both single_BCH and multiple_BCH techniques have reduced the sudden break-down of a CH node concomitantly; they have also considerably improved the network lifetime. Consequently, packet drop is reduced during transmission, giving a rise in data reliability of the system. Furthermore, as the re-clustering time is reduced in the system the network operation time of the system

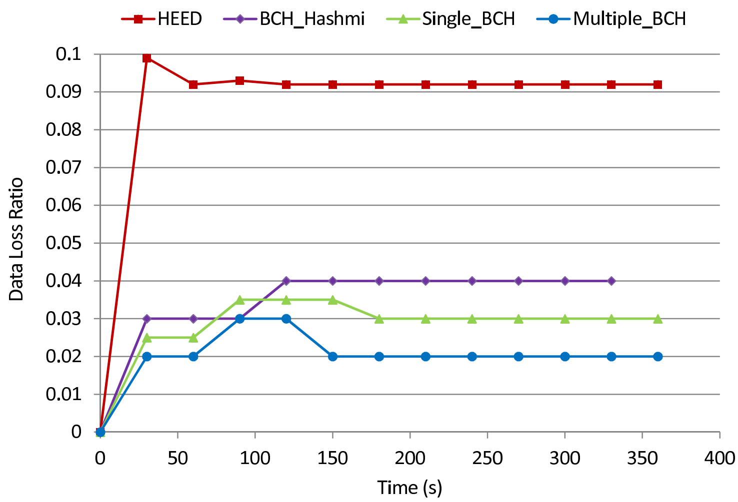

Figure 3.12: Comparison of Data Loss Ratio (DLR) using HEED vs backup clustering schemes for WSN with 200 nodes.

increases, which increases system reliability.

The *t-tests* are performed for the pair-wise selected data to test the significance of the difference in the obtained results for the network lifetime (Fig. 3.10, and Fig. 3.11). For this, each time the data of the HEED protocol and the data of the other schemes at a 95% confidence level are taken. For 200 nodes, *t-test* yielded p-values of 6.3×10^{-73}, 2.5×10^{-131} and 5.5×10^{-63} for single_BCH, multiple_BCH, and BCH_Hashmi schemes respectively, asserting that all are significantly different. Similar p-values were also produced for the WSN with 300 nodes. Again, the significance of the difference in the obtained results from the DLR (Fig. 3.12, and Fig. 3.13) are tested by taking the data of the HEED protocol and data with other protocols at a 95% confidence level. For 200 nodes, *t-test* yielded p-values of 5.2×10^{-14}, 8.4×10^{-15} and 3.2×10^{-12} for single_BCH, multiple_BCH, and BCH_Hashmi schemes respectively, asserting that all are significantly different. Similar significant differences were also found in 300 nodes.

3.5.2.2 With Solar Energy

The performance analysis of the proposed protocol has also been carried out with solar powered sensor nodes. The reasons for incorporating solar powered sensor nodes in the experiment are as follows:

1. Recharging sensor nodes is often very difficult because most of the time they are

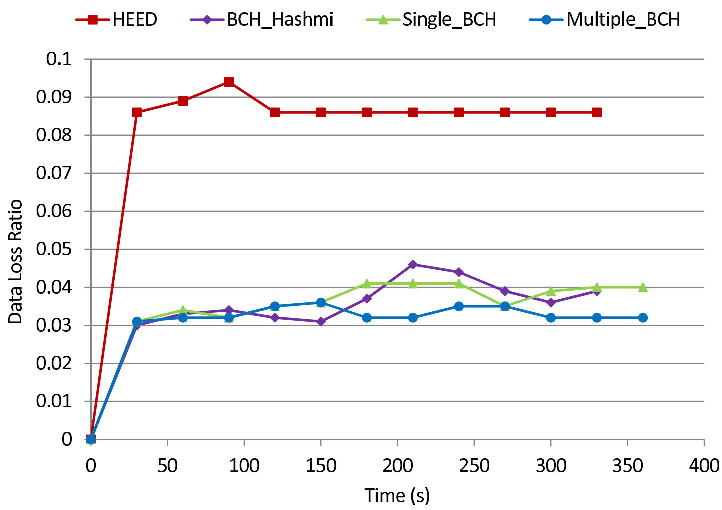

Figure 3.13: Comparison of Data Loss Ratio (DLR) using HEED vs backup clustering schemes for WSN with 300 nodes.

deployed in hazardous and inaccessible areas.

2. Production of sensor batteries and disposal of batteries has an adverse effect on the environment.

Across the globe there is a shift from conventional technology to green technology. It is now a global challenge to reduce carbon emission by industry and thereby reduce the effect of global warming. Therefore, vendors are increasingly encouraged to develop equipment embedded with solar energy, such as solar panels on the roof of a house, solar cars, solar powered wireless sensor nodes, etc.

As alluded to before, as the whole world is merging towards renewable energy, it is essential to investigate the potential of the proposed algorithm to cope with technological changes in the future. For this reason, in addition to the proposed algorithm, two other relevant algorithms (HEED and BCH_Hashmi) have been simulated with solar energy and their results have been compared with the proposed algorithm in terms of energy efficiency and reliability.

According to [138], the solar energy conversion is defined as follows:

$$\eta = \frac{E_s}{E_M} \tag{3.7}$$

where, E_s is the transferred energy to the energy storage and E_M is the power at MPP (Maximum Power Point).

Let, S be the size of a solar panel, η be the solar cell efficiency, T_d be the time of day, and ρ_s be the solar illumination in sunlight. Thus the solar energy transfer in time, T_s is,

$$E_s = \begin{cases} \eta \cdot S \cdot \rho_s \cdot T_s & \text{if } T_s \in T_d \textit{ and } E_{RE} < E_{max} \\ 0 & \text{otherwise} \end{cases}$$

To model the energy behavior, it is necessary to incorporate sensor node energy consumption, energy storage and harvested energy from the solar system. A sensor node starts with full energy, E_{max}. During its lifetime it consumes energy and also performs as a CH node expending energy, as described in (3.1). Let energy consumed by a node at time t be E_c. Harvested solar power can be used in the day time directly and unused solar energy can be stored in a battery or a super-capacitor, provided that the storage is not full. A energy storage device, such as super-capacitor has considerable internal leakage. This leakage varies with the amount of stored energy, the manufacturer, and the individual device. Self-discharge of a super-capacitor could drop voltage below the usable voltage for wireless sensor nodes. The leakage power profile, P_{leak}, can be approximated according to [139], which follows a piecewise linear function.

Two types of energy harvesting and consumption may occur [140]:

1. Harvested solar energy is more than the energy consumed by a solar equipped sensor node; i.e. $E_s > E_c$. This essentially means that a node has an infinite lifetime.

2. Harvested solar energy is less than the energy consumed by a solar equipped sensor node; i.e. $E_s < E_c$. In this situation the node will certainly face a death after a definite period of time.

It is assumed that the energy consumption rate of a node is higher then its solar energy harvesting rate. The simulation in this section follows the same condition. In the experiment of [140], the implication of the energy harvested by a solar cell was observed. The energy gathering profile for typical days of operation of a solar cell was also recorded in [140] for 9 days. The same solar energy generation and consumption model and the parameters are used for experimentation as are shown in Table 3.3. According to the calculation in [140], for a typical AA sized NiMH battery, $E_s - P_{leak}$

Table 3.3: Solar Energy Parameters for Experimental Environment

Parameter	**Value**
ρ_s	23.6 mW
η	0.7 (for NiMH battery of capacity 7.7×10^3J)
P_{leak}	0.6 mW (for NiMH battery)

yields $15.92mW$ at $P_{leak} = 0.6$. Although the storage capacity of a battery degrades with a multiple charge/discharge process, this property is ignored here as it safely meets the energy storage and consumption requirements.

Energy-efficiency measure: Although nodes are equipped with solar cells, not all of them get a chance to harvest energy due to their deployment in regions of unlevel terrain or dense forest. Therefore, 10% of the deployed nodes are intuitively assumed to be capable of harvesting solar energy. Simulation results in Fig. 3.14 and Fig. 3.15 show the network lifetime with $n = 200$ and 300 nodes. According to Fig. 3.14 and Fig. 3.15, an overall lifetime gain has been achieved both in the single_BCH and multiple_BCH over both HEED and BCH_Hashmi protocols for WSNs with 200 and 300 sensor nodes.

For the WSN with 200 nodes, as illustrated in Fig. 3.14, the single_BCH has achieved 41% and 14% over HEED. The results are 37% and 10% without using solar energy. The improvement in the lifetime for the multiple_BCH is 44% and 24% compared with the 41% and 18% without using solar energy. This evidence shows that the proposed scheme offers further improvement using solar energy over HEED as compared to not using it. A similar trend in the results was found when the lifetime improvements are compared for using and not using solar energy between the proposed scheme and the BCH_Hashmi. Overall a 14% improvement in lifetime is exhibited in the proposed method when only 10% of nodes are equipped with solar cells. A similar kind of improvement in lifetime is found for the WSN with 300 nodes, as exemplified in Fig. 3.15. The single_BCH achieves 38% and 20%, while the results are 34% and 18% without using solar energy. The improvement in the lifetime for the multiple_BCH is 45% and

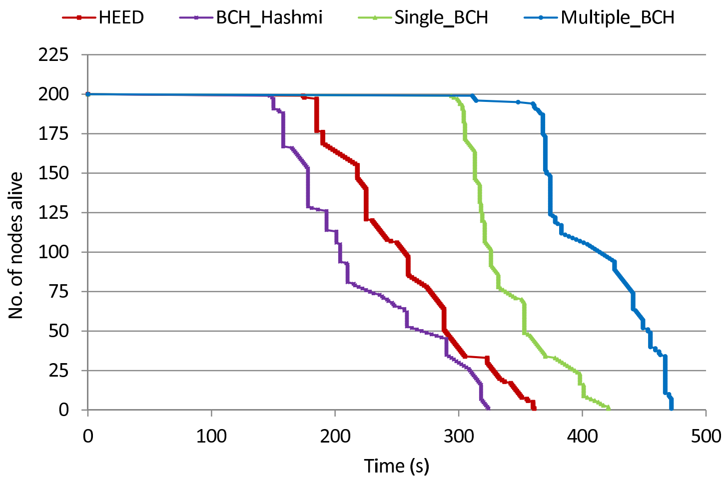

Figure 3.14: Network lifetime using HEED vs backup clustering schemes for WSN with 200 nodes.

25% compared with the achievement of 41% and 22% without using solar energy.

It is apparent from the simulation results that the proposed single_BCH and multiple_BCH schemes significantly increase the network lifetime in both cases (i.e. the time until the first node dies and the time until the last node dies) as compared to the network lifetime of the HEED protocol.

Some of the nodes in the network are equipped with solar cells. These increase the life spans for the BCH nodes, which consequently reduces the number of re-clustering operations required (i.e. the overhead energy consumption). This in turn increases the network's lifetime in terms of the time taken for both the first and last node to die. This has vast implications for real world sensor applications where extended network lifetime is demanded. In the future it is expected that all types of sensor nodes will be embedded with solar cells. Therefore the proposed backup clustering technique has potential for this future technology with respect to energy efficiency.

Reliability measure: For the same network scenarios considered above, we evaluated the data reliability measures. The simulation results in Fig. 3.16 and Fig. 3.17 illustrate the DLR measure for the WSN with 200 and 300 sensor nodes, respectively, using HEED, BCH_Hashmi and the single_BCH and multiple_BCH protocols using (3.6).

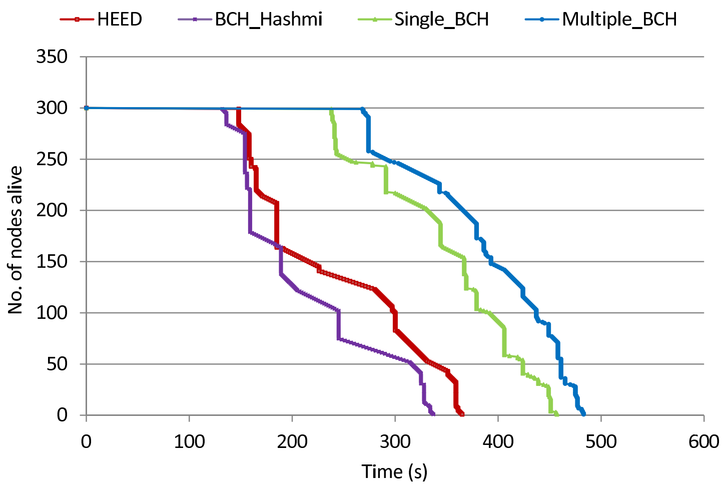

Figure 3.15: Network lifetime using HEED vs backup clustering schemes for WSN with 300 nodes.

The DLR readings (Fig. 3.16 and Fig. 3.17) indicate that both the single_BCH and multiple_BCH schemes have achieved a significant gain compared to the HEED protocol. This gain is 10% more in the respective cases for the WSNs without using solar power, as shown in Fig. 3.12. Considerable average gain in reliability has also been achieved for the single_BCH (54%) and multiple_BCH (16%) schemes over BCH_Hashmi. These improvements are about 12% and 1% more than those achieved for the WSN without using solar power. Similar simulation results are found for the network with 300 nodes, as is shown in Fig. 3.17. Again, the DLR readings are reduced substantially for both single_BCH and multiple_BCH schemes over the HEED and BCH_Hashmi protocols. Compared to the sensor network without using solar power, the reliability of the WSN with solar power for the multiple_BCH has experienced an increase of 3% and 6% over the HEED and BCH_Hashmi protocols respectively, while these increases are about 2% for the single_BCH over the HEED and BCH_Hashmi protocols.

The WSN with 10% of nodes embedded with solar cells has predominantly increased the data reliability of the network. The reason behind this reduced data loss is the effect of the increased network operation time which reduces the re-clustering time. Moreover, as mentioned before, the proposed backup clustering scheme tends to select the BCH close to the center of a cluster. As a result, the network becomes more robust

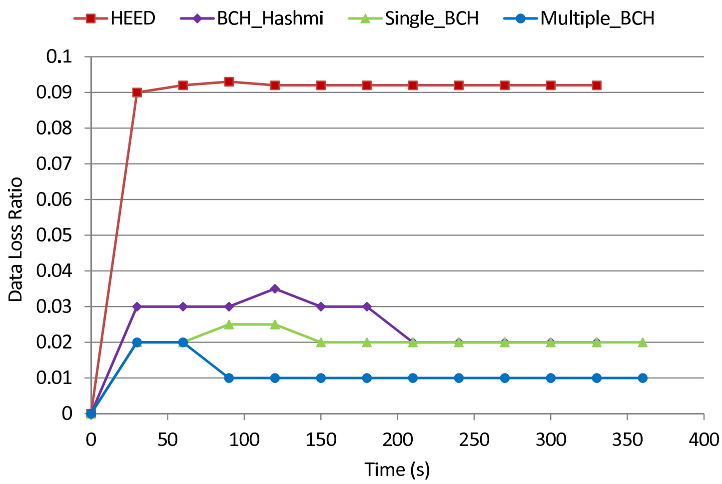

Figure 3.16: Comparison of Data Loss Ratio (DLR) using HEED vs backup clustering schemes for WSN with 200 nodes.

in relation to node failure, which increases the reliable transfer of data. Therefore, it can be interpreted that by introducing solar harvesting cells in part of the network, the network reliability can be significantly increased. This increase in reliability is demanded by many sensor applications.

The *t-tests* are performed for the pair-wise selected data to test the significance difference of these improvements obtained in the network lifetime by the proposed scheme when compared with HEED, both using solar energy and not using it. For this, the data of the HEED protocol and the data from the other schemes at a 95% confidence level is taken. For 200 nodes, the *t-test* yielded p-values of 3.6×10^{-120}, 1.3×10^{-194} and 5.4×10^{-99} for the single_BCH, multiple_BCH, and BCH_Hashmi schemes respectively, asserting that all are significantly different.

Similar trends in p-values were also observed in the network lifetime for the other simulation scenarios, as well as in terms of the reliability for both WSNs compared with the HEED and BCH_Hashmi.

3.5.3 Messaging Overhead Measure

In addition to the tests described above, an experiment was carried out to compare the messaging overhead of the proposed backup clustering scheme with the BCH_Hashmi [55] and HEED. In the simulation, multiple (3 to 4 times) BCH switching took place

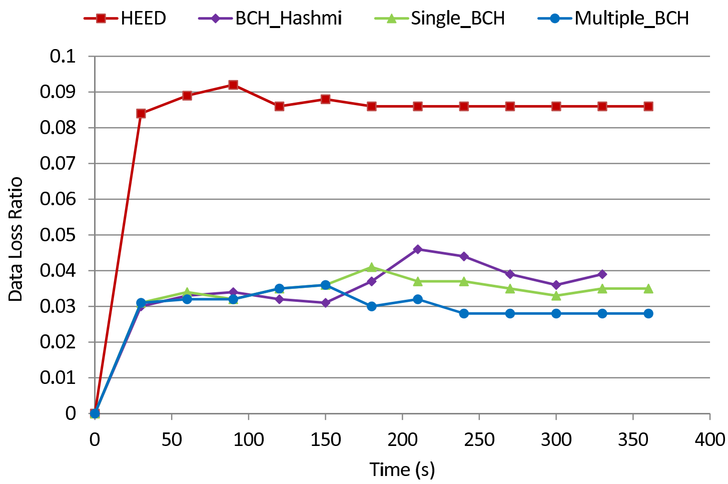

Figure 3.17: Comparison of Data Loss Ratio (DLR) using HEED vs backup clustering schemes for WSN with 300 nodes.

in each cluster for the proposed multiple_BCH scheme. The BCH switching operation in the proposed protocol needs to broadcast a few control messages. Hence, the overall network control traffic due to switching is very low compared to HEED and BCH_Hashmi. As alluded to in section Section 3.4.4, the control messages are comprised of sending a message to the selected BCH, receiving its control message and broadcasting BCH information to its member and the other relevant CH nodes. Tables 3.4 and 3.5 show the control message overhead comparisons for networks without solar power and with solar power, respectively.

Table 3.4: Performance Comparison with Messaging Overhead (nodes without solar power)

Protocol	Message Exchanged	
	300 nodes	200 nodes
HEED	1768	1323
Multiple Backup	1479	1202
Single Backup	1405	1092
BCH_Hashmi	1785	1336

For sensor networks with a large number of nodes, scalability is an important issue. Due to the periodic re-clustering, a large network introduces a large overhead of control messaging. According to Tables 3.4 and 3.5, as the network grows from 200 to 300

Table 3.5: Performance Comparison with Messaging Overhead (some nodes with solar power)

Protocol	Message Exchanged	
	300 nodes	200 nodes
HEED	1794	1345
Multiple Backup	1497	1213
Single Backup	1416	1099
BCH_Hashmi	1809	1356

nodes, the messaging overhead increases by 33% for both HEED and BCH_Hashmi protocols, while the increase is 23% and 28% for the multiple_BCH and single_BCH protocols, respectively. Thus, it can be said that the proposed protocol offers better scalability.

3.6 Summary

In this chapter, an optimal backup cluster head scheme is proposed where the role of a cluster head rotates amongst selected member nodes within the cluster for balanced energy dissipation. This scheme has reduced energy consumption and time needed for frequent re-clustering and has thus enhanced the network lifetime and reliability at the same time. The rotation of the CH role among the member nodes of a cluster can be embedded in any clustering algorithm. Simulation of the proposed scheme, and its comparison with the renowned clustering technique known as HEED and with the only existing backup clustering technique [55], confirmed that by rotating the CH role in a cluster-based network, both the network lifetime and reliability have been improved simultaneously. In addition to this, the proposed technique also requires less message overhead in comparison with the other protocols.

Re-clustering the entire network is not only a resource burden on the nodes, but is also very disruptive to the on-going data sensing and transmission operation. Re-clustering time is usually very large compared to the BCH switching. The data of the whole network is lost during re-clustering, while in our BCH method, only a part of the data is lost during switching time. Therefore, the proposed backup clustering scheme better monitors the field by avoiding loss of important data from a sensor node.

Simulation results have also reflected that our method has produced better performance than HEED and [55] when a portion of the sensor nodes is equipped with a solar cell. This demonstrates the greater suitability of the proposed technique in promoting a sustainable environment. In addition, the selection of BCH and switching of BCH is a distributed process; i.e. they are performed by the respective CH. Therefore, the proposed backup clustering technique is scalable.

After the formation of clusters in the network, a clustering technique generally calculates a routing path using the shortest path based on energy consumption. These techniques usually do not consider link quality and traffic congestion for the development of routing information. However, if link quality and traffic congestion are not taken into account, the minimum energy consumption does not converge to the shortest path due to the re-transmission of the lost packets. In addition, if we include the traffic congestion for the path selection, this reduces the chance of sudden breakdown of a CH node due to transmission of heavy traffic flow. In the next chapter we will introduce a inter-cluster routing scheme that considers packet loss due to link quality and traffic congestion.

Chapter 4

Reliable and Energy Efficient Inter-Cluster Communication Technique

As identified in Chapter 3, an inter-cluster communication path selection strategy plays a significant role in the overall reliability and energy consumption of the network. CHs form the backbone of the crucial inter-cluster communication for the WSN and consume a huge amount of energy. If the same routing path is used repeatedly, then the associated CH nodes of that route will quickly deplete their energy due to relaying large quantity of inter-cluster communication traffic. This is known as a *hot-spot* problem. This expedites the death of some CH nodes, which eventually declines the overall network lifetime. More importantly, the early death of some CH nodes disconnects the CH along with both its cluster and non-cluster members, which degrades the network reliability. The contemporary clustering techniques, such as Leach, HEED [14], PEACH [74] and so on, consider only intra-cluster communication and ignore inter-cluster communication in their clustering process. As a consequence, they generally use a shortest path-based minimum hop count, which can neither minimize energy consumption nor maximize reliability.

It is difficult to ensure reliable data transfer in WSNs because of the unreliable nature of the wireless link quality and the congestion at a CH node. The effect of unreliable link quality is more in the inter-cluster communication than intra-cluster communication, as the inter-cluster communication distance is much higher than the intra-cluster communication distance. In this chapter we present inter-cluster routing protocols based on cost function that analyze all possible inter-cluster communication paths between a source CH and the BS. These protocols make a trade-off between reliability and energy consumption or selection of an optimal routing path, which improves both network reliability and lifetime simultaneously. The real-time updates of the link quality and CH congestion metrics have been introduced for the estimation of the packet loss. The proposed techniques have improved both reliability and network lifetime significantly compared to the contemporary cluster based routing techniques.

First, this chapter by presents the research problem (Section 4.1). Following this, the inter-cluster communication model is elaborated (Section 4.2) and the energy consumption model of the system and the link quality and congestion model are presented. Next we present an energy consumption analysis for routing paths and explain the cost based route selection schemes in the routing path selection techniques (Section 4.3). After that we describe the operation of our routing protocol to achieve a trade-off between reliability and energy efficiency, together with the trade-off protocol operation, the time and message complexities involved in this technique (Section 4.4). Then we present the optimum routing path selection scheme (Section 4.5). Next we present the performance evaluation of the simulation model and its parameters, along with the simulation results (Section 4.6). We conclude by summarizing the chapter (Section 4.7).

4.1 Problem Statement

The proposed efficient inter-cluster routing path selection technique is motivated by observing the imbalanced data forwarding characteristic of the CH nodes, which leads to a *hot-spot* problem. As a result of carrying excessive inter-cluster traffic, CH nodes quickly exhaust energy and the whole network becomes destabilized and data reliability decreases. Traveling the same distance by the minimum hop count path increases the distance between two consecutive stations, which makes signal strength weaker and introduces data loss [119]. Rather than arbitrarily choosing a path based on minimum hop-count metric, it is possible to discover better quality paths with minimum energy consumption. Therefore, a crucial issue is to devise an efficient way to route the data packet from a source CH through intermediate CHs towards the BS, which maximizes energy utilization and minimizes data loss. Although clustering protocol demands periodic re-clustering for balanced energy consumption, repeated re-clustering of the whole network increases the network overhead and eventually decreases the network operation time. A CH node naturally depletes energy faster than a member node. If

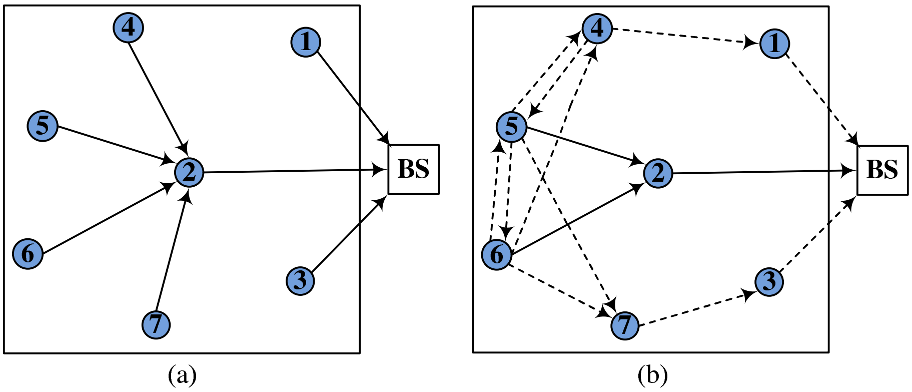

Figure 4.1: Inter-cluster communication by CH nodes (a) forwarding in shortest-path; (b) distributed forwarding in reliable path.

a CH is burdened with excessive inter-cluster traffic to relay, it will fail to perform as a CH until the end of the network operation cycle. To get a better understanding of the problems encountered during inter-cluster communication, consider the example shown in Fig. 4.1(a) and (b), where 7 CH nodes are trying to send data toward the BS. Fig. 4.1(a) explains how CH node 2 is burdened with inter-cluster traffic, and the same is true for CH nodes 1, 2, and 3 in Fig. 4.1(b).

Another important problem arises when more and more CHs try to select the same CH, which is usually the one closer to the BS, to relay their inter-cluster traffic. This type of competition for the same channel by several source CHs increases the chance of collision and interference. According to Fig. 4.1(a), CH nodes 4, 5, 6, and 7 share the same channel with CH nodes 2 while transferring inter-cluster data packet. Consequently, this produces data loss due to collision and hence reduces reliability. For CH nodes 5 and 6, CH node 2 is the closest to the BS, as shown in Fig. 4.1(b). However, CH node 2 experiences interference because of its neighbours' transmission. As a result, the links between $2-5$ and $2-6$ are exposed to a high packet error rate. Better performance could be achieved if CH nodes 5 and 6 choose CH nodes other than 2 to forward their packets. In addition to interference, link quality also deteriorates with environmental noise, obstacles, and so on.

Let us look into this problem of packet loss due to congestion, as illustrated in Fig. 4.1(a). CH node 2 soon becomes congested due to receiving packets from CH nodes 4, 5, 6 and 7. Congestion may also occur at CH node 1, 2 and 3 of Fig. 4.1(b). Re-transmission of the lost packet is the popular mechanism that is usually adopted to increase transmission reliability. However, to ensure reliability of the network a CH node needs to expend extra energy for re-transmission of the lost packet.

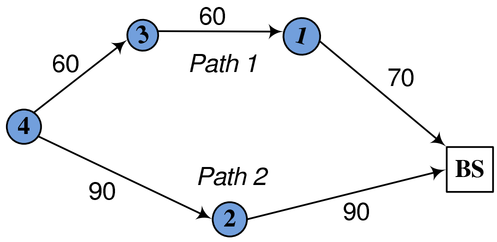

Figure 4.2: Example of multiple inter-cluster routing path with different path lengths.

Another important aspect of the inter-cluster communication made by CH nodes is the hop count. The path with minimum hop count cannot always guarantee minimum and uniform energy consumption amongst CH nodes. Inter-cluster communication is always subject to multi-path fading (d^4 power loss) instead of a free space (d^2 power loss) communication model [12]. If the distance of each link of a minimum hop count path is larger than each link of a maximum hop count path, the total energy consumption of a minimum hop count path can be larger than a maximum hop count path. To better explain the problem, let us consider a network scenario where 4 CH nodes are located in an area, as shown in Fig. 4.2. The distance between CH nodes is represented by connecting edges and is expressed in meters. According to the illustration, node 4 has two alternate paths to reach the BS: *Path 1:* $4 \rightarrow 3 \rightarrow 1 \rightarrow BS$ and *Path 2:* $4 \rightarrow 2 \rightarrow BS$. We follow the same energy model as defined in (2.5) and (2.6) and the values used in Table 3.2, as mentioned in Chapter 3, to calculate the total energy consumption of routing paths in Fig. 4.2.

Path 1: $Total\ (E_t) + Total\ (E_r) = (67 + 67 + 82) + (50 + 50) = 316$ and

Path 2: $Total\ (E_t) + Total\ (E_r) = (136 + 136) + (50) = 322$.

This shows that *Path 1* (maximum hop count path) consumes less energy than *Path 2* (minimum hop count path).

We divide the routing path selection problem into the following two categories,

- *Problem-1*: To achieve a trade-off between reliability and energy efficiency in routing paths.
- *Problem-2*: To determine the optimum routing path.

4.2 Inter-Cluster Communication Model

Here we consider a wireless sensor network where sensors are randomly distributed over a two-dimensional area in which a BS is placed at one corner. The sensors' primary task is to monitor events and report data periodically. The location information of the nodes is unknown to each other, as we have assumed that they are not equipped with GPS or positioning algorithms. As a result we cannot use location information to take a routing decision. The nodes are capable of communicating with different power levels for inter-cluster communications. The links are considered bi-directional and symmetric; that is, two nodes can communicate using the same transmission power level. Nodes are assumed to be stationary or have limited mobility. To capture the realistic network model, we have also adopted re-transmission due to all kinds of packet loss.

4.2.1 Energy Consumption Model

In the clustering scheme, nodes are organized into clusters, where member nodes transmit their data packet to their respective CH node during each data transfer cycle, using TDMA. This ensures efficient use of bandwidth and minimal inter-cluster interference. CH nodes aggregate data and use a routing protocol to compute inter-cluster paths for multi-hop communication towards the BS. In order to prevent message collisions, each CH again uses a CSMA MAC scheme to communicate with other CHs at the same time. The BS is responsible for receiving data from CHs.

During the intra-cluster communication, the distance between member nodes and the CH ($d_{non-CH,CH}$) is small and hence we use a free space (fs) model. On the other hand, the distance between two CHs or between CH and BS ($d_{CH,CH/BS}$) is always greater than the characteristic distance d_0 used in (2.5) and hence, a multi-path fading (mp) model is used. Thus, inter-cluster communication experiences $d^4_{CH,CH/BS}$ power loss [12] instead of free space ($d^2_{CH,CH/BS}$) power loss. We consider all kinds of nodes' energy expenditure, such as the energy required for electronic circuitry, data aggregation, data transmission and reception. The energy required for a l-bit message transmission and reception over a distance d is already defined in (2.4), (2.5) and (2.6) of Section 3.2.

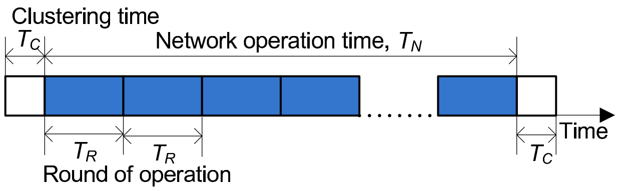

Figure 4.3: Timeline of clustering and network operation rounds

During the network operation time, the CH node collects data from its member nodes, aggregates all data, and sends the aggregated data either to the next CH or the BS. As illustrated in Fig. 4.3, T_C and T_N represent the clustering and network operation time, respectively. The link condition and congestion at the CH node change with time due to several factors. To accomplish the routing path selection task efficiently, it is essential to get updated information as to link quality and CH congestion at regular intervals. Therefore, each T_N is again divided into R number of network operation rounds. Here, T_R represents the network operation round, after which all CHs broadcast their necessary parameters. If E_{CH} is the energy required (without relaying any multi-hop traffic) by a CH in a unit of time, during T_R time a CH consumes an energy of $T_R \times E_{CH}$. In each network operation time it consumes an energy of $T_N \times E_{CH}$. To use a CH node, CH_j, as an intermediate CH of a route r, it has to have enough energy at time t to sustain R rounds of network operations; i.e.

$$E_{j,extra}(t) = E_{j,res}(t) - (T_N - xT_R) \times E_{CH} \tag{4.1}$$

where, x is the number of elapsed T_R rounds of any network operation time. If $E_{j,extra}(t) \leq 0$, CH_j is unable to perform as a relay node. Thus, by excluding a CH that does not possess sufficient energy to sustain R rounds of network operation from being used in the routing path, we can safeguard a CH from sudden breakdown due to energy depletion. Eq (2.5) implies that the energy required to relay multi-hop traffic by a CH node is directly proportional to the distance of the next CH or BS. Hence, a route composed of links with shorter distances can also minimize energy consumption.

4.2.2 Link Quality and Congestion Model

In this section we present link quality and congestion metrics for inter-cluster communication path selection. The usage of these two metrics in our proposed algorithm helps to avoid poor quality links and a congested CH. Interference in a particular transmission link is caused by signal transmissions of other nearby nodes; this is accounted for as noise. Bit Error Rate (BER) assesses the full end-to-end performance of a system, including the transmitter, receiver and the wireless medium between these two. Lee et al. [141] derived the following expression to calculate BER:.

$$BER = 0.5 \times erfc(\sqrt{\frac{P_r \times W}{P_n \times T_B}}) \tag{4.2}$$

where, P_r is the received power; W is the channel bandwidth; P_n is the noise power; T_B is the transmission bit rate and $erfc$ is the complementary error function. The Packet Error Rate (PER) is the number of incorrectly received data packets divided by the total number of received packets. A packet is declared incorrect if at least one bit is erroneous. The expectation value of the PER is denoted as packet error probability p_p, which for a data packet length of M bits can be expressed as

$$p_p = 1 - (1 - p_e)^M \tag{4.3}$$

where, the bit error probability, p_e is the expectation value of the BER. Now, as we know the packet size, it is possible to calculate Packet Loss Ratio (PLR) from PER. In this study, we used PLR to denote the link quality between each CH-CH and CH-BS link of the network.

Let, $L_{ij}(t)$ be the link quality between CH_i and CH_j at time t. Here, the link quality is expressed in terms of PLR. The value of $L_{ij}(t) = 0$ corresponds to the ideal case where there is no packet loss, while $L_{ij}(t) = 1$ indicates that no link exists between CH_i and CH_j.

Each CH again experiences data loss due to congestion, the buffer of which reflects this status. If the buffer of a CH is full, it will be unable to forward its traffic to the next CH or BS and drop packets. Thus, congestion at the CH node causes packet loss and congestion at multiple intermediate CHs of a route, decreasing performance significantly. Let, B_{in} and B_{out} be the rates of the incoming packet in the buffer and the outgoing packet from the buffer of a CH, respectively. Then, the number of packet drops due to congestion at a CH at time duration of T_R is

$$\{(B_{in} - B_{out}) \times T_R - B_{size}\} \; when \, (B_{in} - B_{out}) \times T_R > B_{size}.$$

Here, B_{size} is the buffer size of a CH node. Hence, if the packets are dropped, the packet loss rate due to congestion at time t can be defined as

$$B(t) = \frac{B_{size} - (B_{in} - B_{out}) \times T_R}{B_{in} \times T_R} \tag{4.4}$$

The negative value of $B(t)$ indicates the packet drop rate due to buffer overflow at the CH node. Thus, to increase reliability by minimizing data loss, a routing path must carefully exclude congested CH nodes for relaying multi-hop data.

4.3 Routing Path Selection Techniques

In a multi-hop sensor network, a CH node usually plays the dual role of data sensor and data router. Here, we calculate the total packets generated and transmitted by all CHs that constitute a route, after the source CH_i first sends out P packets. To estimate the energy consumption by an end-to-end route, we consider congestion at the CH node and link reliability factors. As mentioned before, the PLR of a link expresses the link quality and the CH node's buffer status indicates its congestion level. This knowledge is used to calculate the cost of the entire routing path and thereby selecting the next-hop towards the BS. As node energy, link quality, and congestion are time varying in nature, a periodic update of these matrices is necessary.

For each one-hop transmission, an acknowledgment (ACK) packet is sent back when one data packet is received. The loss of an ACK packet also causes a re-transmission. Let each CH of the network generates P packets per unit of time where each packet is of l_1 bits and the size of the ACK packet is l_3 bits. Since there could be many routes from a CH node CH_i towards the BS, let r represent one of them. The route r may comprise of a set of links, denoted by K_{ri}, each of which has an independent PLR value for link quality (L_{rij}, where i and j indicate i_{th} source and j_{th} indicates destination CHs). If we consider m number of re-transmissions due to packet loss from poor link quality of the route r, then the number of total packets that need to be re-transmitted by CH_i through the first link of route r:

$$P^L_{rij} = P \sum_{s=1}^{m} L^s_{rij} \tag{4.5}$$

Again, the same route path r can incur packet loss due to congestion at each destination node j, including the BS, which is represented by B_{rij}. Source CH_i incurs packet loss due to congestion while transmitting P packets towards the BS. In this case, the total packets need to be re-transmitted by CH_i to CH_j through the route r and considering m re-transmission:

$$P_{rij}^{B} = P \sum_{s=1}^{m} B_{rij}^{s} \tag{4.6}$$

Considering data loss due to both link quality and congestion, and based on (2.5), the energy required to transmit P packets by CH_i to CH_j through the first link of the route r is

$$P_{rij} = Pl_1(e_{elec} + \varepsilon_{mp} d_{ij}^4) + Pl_1(e_{elec} + \varepsilon_{mp} d_{ij}^4) \sum_{s=1}^{m} (L_{rij}^{s} + B_{rij}^{s}) \tag{4.7}$$

where, d_{ij} represents the distance between CH_i to CH_j. Link quality varies for each link. Considering both link quality and congestion, the total energy required ($E_{rit}(D)$) to transmit all multi-hop data packets represented by D up to the BS, following all links of the route r for source CH_i is

$$\begin{aligned} E_{rit}(D) &= Pl_1 \sum_{i=1}^{Kri} (e_{elec} + \varepsilon_{mp} d_{i,i+1}^4) \\ &- Pl_1 \sum_{j=1}^{Kri-1} (e_{elec} + \varepsilon_{mp} d_{j+1,j+2}^4) \sum_{i=1}^{j} (L_{r,i,i+1}^{m} + B_{r,i,i+1}^{m}) \\ &+ Pl_1 \sum_{j=1}^{Kri} ((e_{elec} + \varepsilon_{mp} d_{j,j+1}^4) \sum_{s=1}^{m} (L_{r,i,i+1}^{s} + B_{r,i,i+1}^{s})) \\ &- Pl_1 \sum_{j=1}^{Kri-1} ((e_{elec} + \varepsilon_{mp} d_{j+1,j+2}^4) \sum_{i=1}^{j} (L_{r,i,i+1}^{m} + B_{r,i,i+1}^{m}) \\ & \sum_{s=1}^{m} (L_{r,i+1,i+2}^{s} + B_{r,i+1,i+2}^{s})) \end{aligned} \tag{4.8}$$

Note that full derivation of $E_{rit}(D)$ has been provided in Appendix A.

Additionally, the destination CH sends one ACK packet to the source CH for each successful reception of the data packet through the same link. Hence the energy required ($E_{rit}(A)$) to transmit all ACK packets, indicated by A, that are generated in the network by the intermediate CHs constituting the route r due to generation of P packets by source CH_i is

$$E_{rit}(A) = Pl_3 \sum_{j=1}^{Kri} (e_{elec} + \varepsilon_{mp} d_{j,j+1}^4) \prod_{i=1}^{j} (1 - L_{r,i,i+1}^{m} - B_{r,i,i+1}^{m}) \tag{4.9}$$

Note that detailed derivation of $E_{rit}(A)$ is given in Appendix A.

Therefore, the total transmission energy required (E_{rit}) due to generation of P packets by the source CH_i to the BS using the link r is

$$E_{rit} = E_{rit}(D) + E_{rit}(A) \tag{4.10}$$

Again, all $(Kri - 1)$ intermediate CH nodes of the route r consume energy in receiving the data packets before forwarding them to the next CH node. In this case, based on (2.6), the total energy required ($E_{rir}(D)$) for receiving data packets by intermediate CHs is

$$\begin{aligned} E_{rir}(D) &= (Kri-1)Pl_1 e_{elec} - Pl_1 e_{elec} \sum_{i=1}^{Kri-2} (L^m_{r,i,i+1} + B^m_{r,i,i+1}) \\ &+ Pl_1 e_{elec} \sum_{i=1}^{Kri-1} \sum_{s=1}^{m} (L^s_{r,i,i+1} + B^s_{r,i,i+1}) \\ &- Pl_1 e_{elec} \sum_{i=1}^{Kri-2} (L^m_{r,i,i+1} + B^m_{r,i,i+1}) \sum_{s=1}^{m} (L^s_{r,i+1,i+2} + B^s_{r,i+1,i+2}) \end{aligned} \tag{4.11}$$

Also, CHs of the route r consume energy for reception of the ACK packet, which requires total energy of

$$E_{rir}(A) = Pl_3 e_{elec} \sum_{j=1}^{Kri-1} \prod_{i=1}^{j} (1 - L^m_{r,i,i+1} - B^m_{r,i,i+1}) \tag{4.12}$$

Therefore, total receiving energy required for the route r due to the reception of P packets and their $ACKs$ is

$$E_{rir} = E_{rir}(D) + E_{rir}(A) \tag{4.13}$$

4.4 Trade-off between reliability and energy efficiency of routing path

The proposed inter-cluster routing technique is applicable to any cluster-based WSN. Therefore, this scheme starts its operation immediately after the initial clustering phase is carried out. A pro-active routing based on beacon update is used for calculating the cost of the routing path and of taking the routing decision. In the rest of this section, the routing path selection scheme is elaborated with analysis. During the clustering phase, sensor nodes are partitioned into different clusters, where each cluster gets a CH. Member nodes send data to the CH periodically using TDMA scheduling. On the other hand, all CH nodes in the network form a communication backbone to transport data towards the BS using multi-hop communication. At each operation round, upon receiving the updated information about the link condition and congestion status of the intermediate CH nodes, a source CH takes the step of determining the cost of the path.

We devise the following cost function to select the possible routing path r by a source cluster head, CH_i:

$$\begin{aligned} f(Path\ Cost) &= \alpha(Total\ Energy\ for\ packets\ transmission) + \\ &(1-\alpha)(Total\ Energy\ for\ packets\ re-transmission) \\ f(CH_{ri}) &= \alpha \times E_{ri}(P) + (1-\alpha) \times E_{ri}(Q) \\ &where,\ 0 \leq \alpha \leq 1 \end{aligned} \tag{4.14}$$

Here, P indicates the packets needing to be transmitted and Q represents the packets required to be re-transmitted due to packet loss from poor link quality and congestion.

- $E_{ri}(P)$ denotes the energy required by a routing path without considering packet loss. Here, α is a weighting factor that makes a trade-off between reliability and energy efficiency.
- $E_{ri}(Q)$ denotes the extra energy required by a routing path due to re-transmission of lost packets. We consider m number of re-transmissions for the lost packet.

The value of α can be determined by considering the service requirements of users' applications. For example, the value of $\alpha = 1$ of (4.14), gives the highest priority to those applications that demand energy efficiency; the value of $\alpha = 0$ satisfies the demand of the applications that are sensitive to data losses and require reliable transfer of data. $\alpha \epsilon [0, 1]$ makes a trade-off between reliability and energy efficiency. For a particular value of α, the route with minimum energy consumption is considered the best path and ranked as 1, provided that all of its relay CH nodes have the required minimum energy E_{min}. In the same way, all its routes and the routes for the other CHs are ranked.

4.4.1 Protocol Operation

In this section we present the operation of our proposed routing protocol, which achieves a trade-off between reliability and energy efficiency. We named this protocol the Multi-hop Route Selection Scheme (MRSS). The route selection process starts just after the clustering process. MRSS creates a routing backbone composed of a set of CH nodes that propagates data towards the BS. As the MRSS follows a pro-active route selection strategy to support periodic data generating networks, it needs periodic updating. At the beginning of each network operation round (T_R), CH nodes broadcast a beacon packet using the CSMA MAC protocol to other CHs to inform them of its updated status. The beacon packet contains information regarding its current remaining energy, congestion and link quality toward its neighbouring CH. Each neighbouring CH collects this information and stores it in a local table.

In each round, the CH nodes compute the path cost based on the metrics provided using the MRSS algorithm. The responsibility of each intermediate CH is to forward the data packet through the selected path. Although establishing and re-computing the routing path introduces extra messaging overhead, this is less when compared to the re-clustering of the whole network. This is because only CH nodes are involved in the messaging process and only a small number of nodes (e.g. around 5% if the nodes are selected as CH nodes, as mentioned in [12]) act as CH nodes in the network.

The source CH only notifies those intermediate CHs, that will be used for this purpose by sending a Route Reply (RR) packet. After receiving ACK from the intermediate CHs, the source CH node starts sending a packet using the best route. Thus, the protocol can be illustrated in the as following steps:

- Each CH node broadcasts its remaining energy, the PLR of a link and the congestion using beacon packets.
- All CH nodes store this information in a local table for possible use in route computation.
- Updating of these parameters take place at the beginning of each round of the network operation.
- Based on the received parameters, each CH node estimates the route based on

the cost function. As alluded to in section 4.2.1, the period of a route estimation is determined by the time of a network operation round.

- The source CH node sends multi-hop relay packets using the best route.
- If no beacon packets are received from the previous neighbour, it is considered that a link or a CH has failed. Then the source CH will select the next best route for the rest of the transmission.

4.4.2 Time and Message Complexities

Each CH node requires only the information from the neighbouring CH nodes within its transmission range. Therefore, information gathering from the neighbourhood can be carried out in constant time. Hence, the time complexity of the proposed algorithm is constant as local computation time is negligible. In MRSS, only the CH nodes send an update message in each network operation time. This is a small and constant-length control message that is destined for only CH nodes. If N is the total number of CHs in the network, T_R is the messaging interval and R is the number of rounds, the total messaging overhead in a network operation time is $N \times R$. Thus, the overhead in transmitting and receiving the control messages across the network is $O(NR) \cong O(N)$, as $R \ll N$. This shows that the control overhead is low, which meet our design goal.

4.5 Optimum Routing Path Selection Scheme

The trade-off between reliability and energy efficiency in the routing protocol, as discussed in Section 4.4.1, requires the value of α to choose a routing path. However, to achieve an optimized performance of both reliability and energy consumption, we need to find a suitable value of α. In (4.5) and (4.6) of Section 4.3, we have encoded the packet loss due to link quality and traffic congestion in terms of re-transmission energy. We have represented the path cost function in terms of the energy consumption required for packet transmission and re-transmission in (4.14). This indicates that reliability and network lifetime can be improved simultaneously if we can determine the routing path that requires minimum energy consumption. Therefore, for a particular routing path, (4.14) can be represented as an optimization problem for calculating a value of α, which will minimize the overall energy consumption. The objective function for the optimization of (4.14) for a particular routing path r can be formulated as

$$\begin{aligned} E_{ri} = \quad & Minimize \quad f(CH_{ri}) \\ & subject\ to \quad 0 \leq \alpha \leq 1 \end{aligned} \tag{4.15}$$

The path identified by K_r, which provides the minimum value of E_{ri}, will be selected as the optimum routing path and can be defined as

$$K_r = \arg\min_{\forall r}(E_{ri}) \tag{4.16}$$

4.6 Performance Evaluation

4.6.1 Simulation Model and Environments

In this section we evaluate the performance of both the MRSS (trade-off) and optimal routing protocols in terms of data transmission reliability as well as energy efficiency via simulations. TOSSIM (A simulator of TinyOS) is used to implement our proposed MRSS and optimum route selection schemes on top of HEED. The TinyOS beaconing approach constructs a breadth-first spanning tree rooted at the BS. For inter-cluster routing information, the beaconing approach is applied to only the CH overlay, rather than the entire network. Simulation is carried out by sensor network topologies with 200 nodes deployed in a 200×200 area. The square-shaped simulation area is chosen to achieve a longer inter-cluster path and higher hop count. We do not consider that CH nodes can adjust the transmission range during their inter-cluster communication. The BS is assumed to have unlimited power supply. Each sensor node generates data packets periodically and at a constant rate. For a fair comparison, the network topologies, node distribution and node energy distribution were kept identical across all protocols. The lossy radio model is considered to simulate a more realistic and practical link. The Simulation parameters are kept same as listed in Table 3.2.

As mentioned previously, two performance metrics are evaluated here. These are: reliability and energy consumption. For the energy consumption comparison, we calculate the lifetime (both the time until the first node dies and the time until the last node dies) of the entire network. Then, as the reliability measure, we calculate the data loss ratio (DLR) of the network using HEED, HEED with MRSS protocol, and HEED with an optimum route selection scheme using (3.6). The DLR is a ratio of the difference of total data sent by the sensor nodes and received at the BS to the total data sent by the sensor nodes, which has been defined in Section 3.5.

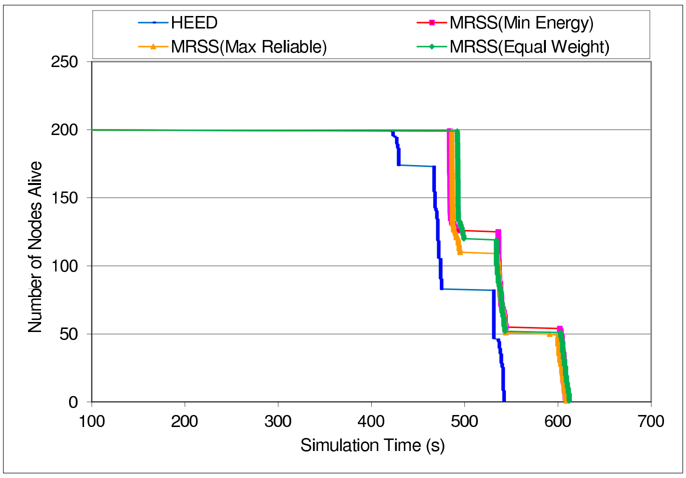

Figure 4.4: Network lifetime using HEED vs MRSS

4.6.2 Simulation Results

The simulation results of our proposed two routing schemes are presented here. First, we showed the performance of the MRSS routing scheme that achieves a trade-off between reliability and energy efficiency. For this, we performed experiments with the MRSS scheme for the minimum energy path, the maximum reliable path and for the path, which gives equal weightage to reliability and energy consumption. Following this we presented the simulation results of our optimum routing scheme.

4.6.2.1 Trade-off between Reliability and Energy efficiency

At first, we evaluate *Problem-1* that is addressed in the Section 4.1.

Energy efficiency measure: In the simulation, re-clustering took place 5 to 8 times for HEED and about 3 to 5 times in the case of the MRSS scheme. The MRSS with *minimum energy consumption* and *maximum reliability* route update messages in each network operation round have been simulated. According to Fig. 4.4, MRSS with minimum energy path (*i.e.* $\alpha = 1$) gained 14% increase in lifetime over HEED in both the case of first node and last node death (*i.e.* $\alpha = 1$). Whereas, in the MRSS with the maximum reliable path (*i.e.* $\alpha = 0$), lifetime gain is 6% and 13% for the first node and last node death, respectively. With $\alpha = 0.5$, meaning giving equal weight to reliability and energy consumption, the lifetime achievement is 14% and 12% for the first node and last node death, respectively. These lifetime gains in MRSS over HEED are achieved for several reasons. Firstly, HEED uses a minimum hop count as a cost function to determine the routing path, which does not give a guarantee of minimum energy consumption, whereas the MRSS gained substantial energy savings due to the considerable reduction in packet drops. Secondly, the MRSS balances energy dissipation among CH nodes while relaying inter-cluster traffic. Finally, the MRSS minimizes frequent re-clustering process, which requires more energy. This result suggest that an efficient routing path selection has a considerable impact on prolonging the network lifetime. Moreover, it is noticeable that more than 10% of the nodes experienced delayed death in the minimum energy path compared to the maximum reliable path.

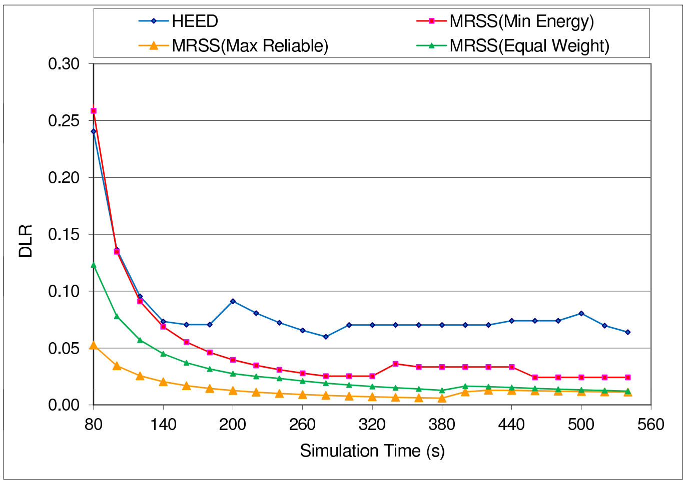

Figure 4.5: Data loss ratio of HEED vs MRSS

Reliability measure: As shown in Fig. 4.5, the DLR drops heavily using the MRSS, when compared to HEED. Using the MRSS with minimum energy path (*i.e.* $\alpha = 1$), the DLR gradually decreases, improving up to 66% in the end, compared to HEED. The maximum drop of the DLR occurs when the route with maximum reliable path (*i.e.* $\alpha = 0$) is selected. In this case, improvement is about 78% in the beginning and about 84% in the end. For $\alpha = 0.5$, the DLR decreases about 50% in the beginning and about 83% in the end. The reason for the reduced data loss when using the MRSS protocol is that the source CH always selects the route comprised of highly reliable links and less congested intermediate CHs. The MRSS reduces frequent re-clustering and thereby extends network operation time. Therefore, the BS receives more data compared to the HEED. However, to establish and maintain the routing path, periodic update messages are broadcasted by CHs only and the overhead is always low. This is because only a few nodes of the whole network act as a CH and, as shown in Fig. 4.4, the lifetime increases considerably for all variations of the MRSS. This also indicates that the route update messaging overhead is far less when compared to the messaging overhead (due to frequent re-clustering) that takes place in the HEED clustering protocol. The simulation results as reflected in Fig. 4.4 and Fig. 4.5 confirm that our inter-cluster routing scheme improves both reliability and the network lifetime over any cluster-based routing protocol. By adjusting the value of α between 0 and 1, we can achieve energy efficiency by compromising data loss rate or vice versa.

4.6.2.2 Optimum Routing Path

We now evaluate *Problem-2* that is addressed in the Section 4.1.

Energy efficiency measure: In the simulation, re-clustering took place 5 to 8 times for HEED and about 3 to 5 times in the case of the optimum routing scheme. We found that at $\alpha = 0.1$, our routing path selection scheme works optimally by ensuring that minimum energy is required for transmission and re-transmission of packets due to their loss. According to Fig. 4.6, the optimum routing scheme gained a 14% increase in lifetime over HEED, both in the case of the first node and last node death. These lifetime gains in optimum routing scheme over HEED are achieved for those reasons set out in Section 4.1.

Reliability measure: The simulation result (Fig. 4.7) shows that the overall DLR drops heavily using the optimum routing scheme compared to HEED. Using the optimum routing scheme with $\alpha = 0.1$, the DLR gradually decreases, which is an improvement of about 48% in the beginning and 83% at the end when compared to HEED. The reason for this reduced data loss from using the optimum routing protocol is that the source CH always selects the route comprised of highly reliable links and less congested intermediate CHs. This also reduces the sudden death of a CH by preserving sufficient energy in a CH node to continue its duty; i.e. aggregation and transmission of packets from its non-member nodes. The optimum routing scheme reduces frequent re-clustering and thereby extends the network operation time. Therefore, for the rea-

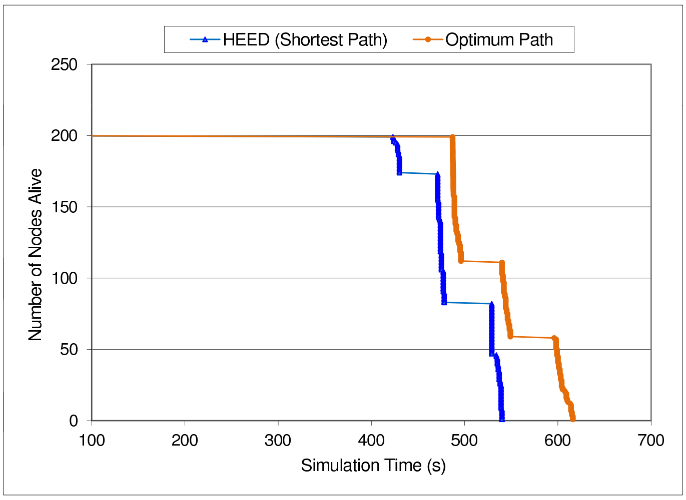

Figure 4.6: Network lifetime using HEED vs Optimum routing

sons set out in the previous section, the BS receives more data as compared to HEED. The simulation results, as reflected in the results shown in Fig. 4.6, and Fig. 4.7 confirm that our inter-cluster routing scheme simultaneously improves both reliability and the network lifetime over any other cluster-based routing protocol.

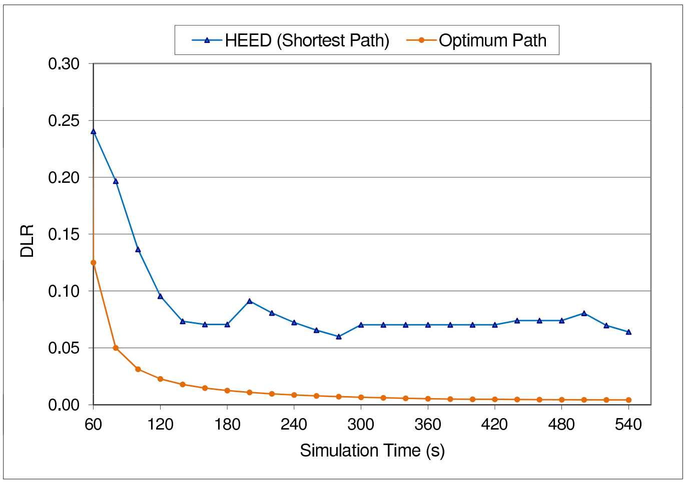

Figure 4.7: Data loss ratio of HEED vs Optimum routing

To test the significance of the difference in lifetime (Fig. 4.6), we selected data from the proposed optimal routing scheme and the HEED scheme. The *t-test* yielded a p-value equal to 0 at a 95% confidence level. Again, we tested the difference in the results for the DLR (Fig. 4.7) between the optimal and HEED routing schemes. In this case, the *t-test* yielded p-values of $p < 6.3 \times 10^{-15}$ at a 95% confidence level. For both reliability and network lifetime this validates that the performance differences are statistically significant.

4.7 Summary

An inter-cluster routing path selection framework for the clustered WSN has been presented in this chapter. The proposed schemes can be applied on top of any clustering scheme to achieve either a trade-off between reliability and energy efficiency in the network or to select the optimum inter-cluster routing path. A cost function-based routing path selection mechanism has been devised that takes into account both the link quality and congestion at the CH node as performance metrics. In the proposed scheme, a source CH is able to select the desired inter-cluster route without the help of the BS. Here, routing path estimation and selection is done proactively, based on real-time updated information about the link quality and congestion. Due to the careful selection of the CH nodes that comprise a routing path, the risk of node failure has been reduced and thereby the data loss is reduced. The simulation results have revealed that both the MRSS and optimum route selection schemes show better performance in terms of network reliability and energy efficiency.

The CH nodes construct the backbone of the inter-cluster communication of a WSN. If the number of CH nodes increases, the inter-cluster communication traffic in the network will usually increase. This will also increase the chance of packet drop due to signal interference and collision. Thus, the overall energy consumption of the network will increase. On the other hand, if the number of CH nodes decreases, again the intra-cluster communication energy consumption will increase due to the need for longer transmission ranges. Therefore, it is necessary to find an optimum number of clusters for a WSN. The existing literature presented in Section 2.2 has exhibited that the techniques for determining the optimal number of CHs emphasis energy efficiency for uniform node distribution but not link quality and traffic congestion. All the available techniques have calculated the optimal cluster number for a WSN prior to the network deployment. They consider these predetermined CH numbers at the time of organizing the uniformly distributed nodes into clusters (a hierarchical structure of a network). However, to obtain the optimality of a WSN in terms of reliability and network lifetime in a real environment, it is essential to determine both CHs and their organization during deployment. So far in the literature there does not exist such a technique. In the next chapter we will introduce a joint optimal clustering technique (JOC), which optimizes both the number of clusters and the clustering process by considering the technique developed in this chapter for inter-cluster communication.

Chapter 5

Joint Optimization of Number and Allocation of Clusters for WSNs

The estimation of the optimal cluster number, as identified in Chapter 4, is one of the challenging aspects for a WSN. The CH nodes form a backbone for the cluster-based network, where determining an optimal number of backbone nodes is a NP-complete problem [58]. The existing clustering techniques for determining the optimal number of CHs are based on an assumption of uniform node distribution and do not consider link quality and traffic congestion. As their determination process is isolated from the clustering process, they also do not consider the aspects of the deployment context. This makes the optimum cluster number determination process and clustering techniques inconsistent. Separate processes for each of them does not guarantee their optimization due to the variation between cluster number determination and clustering at the deployment time. Addressing this gap requires a determination of the cluster number and clustering process during deployment in a real context.

Therefore, in this chapter, we first determine the optimal cluster number for multi-hop WSNs considering link quality and traffic congestion for uniformly distributed nodes. This analytical solution and its simulation results gives us an insight into the optimal cluster number determination process. This leads us to introduce a novel technique for jointly optimizing the number of clusters and clustering process (JOC) that considers link quality and traffic congestion so that both reliability and energy efficiency are maximized. As a result of the application of the node degree in the CH selection process and the consideration of real world deployment, the JOC is suitable for both uniform and non-uniform node distributions. The simulation results exhibit that our proposed JOC significantly improves network lifetime and reliability compared with the most popular and widely used clustering technique; namely HEED.

The organization of this chapter is as follows. We first start with the optimum cluster determination technique for uniform node distribution and describe it in Section 5.1. This section includes a theocratical modeling for the inclusion of link quality and a performance comparison with simulated results. Following this we present our joint optimization for cluster numbers and their allocation in Section 5.2. This section describes techniques for the joint performance of the cluster numbers and their organization. Performance of the proposed JOC technique via simulation is also presented in this section. Finally, Section 5.3 summarizes the chapter.

5.1 Determination of Optimum Cluster Number Considering Link Quality

5.1.1 System Model

We consider that n nodes are distributed uniformly (Fig. 5.1) over a large sensing area $A(a \times a)$ according to a homogeneous spatial Poisson process with intensity σ. Hence, the number of nodes in such an area is also a Poisson random variable, N, with mean σA, i.e., the expected value of N, $E(N) = \sigma A$. The nodes are quasi-stationary, location unaware and have similar capabilities (processing/communication). A node becomes a CH with a probability p, which means that a total of np nodes will become CHs on average.

The energy required for l-bit message transmission and reception over a distance d is already defined in (2.4), (2.5) and (2.6) of Section 3.2. The strategy for cluster-based routing and MAC protocols used in intra and inter-cluster and CH to BS communication are also articulated in the above mentioned section. As the BS has an unlimited energy supply and it already knows the basic parameters of the deployed sensor nodes, we can leave the determination process of the optimal cluster number to the BS. This process is articulated in the next section, which is an important part of the overall network clustering process.

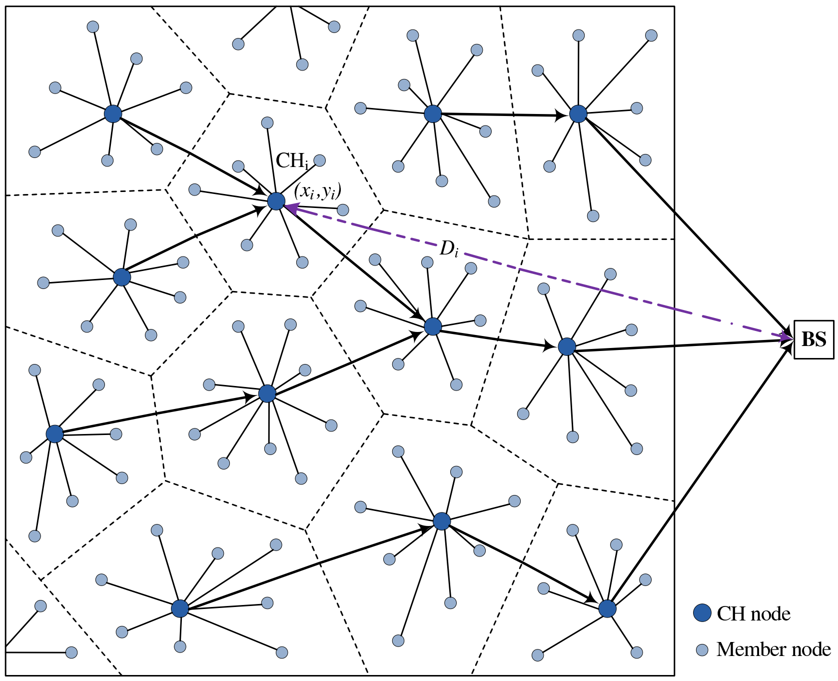

Figure 5.1: Example of uniform node distribution in a square area with redundant inter-cluster communication path.

5.1.2 Cluster Number Analysis

In this section we explain the determination process of the optimal cluster number, where we follow the same cluster analysis process as described in [2]. However, we differ from [2] in that both intra and inter-cluster communication cannot consume energy according to the energy model represented by (2.4). For the energy model alluded to in the above section, we need to use both (2.4) and (2.5) for calculating intra and inter-cluster communication cost, respectively. Moreover, as inter-cluster communication covers a larger distance when compared to intra-cluster communication, it is more likely to suffer from data loss due to poor link quality. Therefore, in our analysis we consider a more realistic energy consumption model by introducing the packet loss due to poor link quality.

Let E_{intra} be the total energy consumed by all non-CH nodes when transferring l-bit of data to the CH node of a particular cluster. According to our assumption described in Section 5.1.1, there are np numbers of clusters in the sensing area. Therefore, according to [2] and for a given n nodes, the total intra-cluster energy consumption by all member nodes to communicate l-bit of data to their respective CH is given by

$$E[C_{intra}|N = n] = 2n(1 - p)e_{elec} + \frac{n\varepsilon_{fs}(1 - p)}{\pi\sigma p} \tag{5.1}$$

Let us begin analyzing the energy spent by inter-cluster communication. D_i is the distance between a cluster head node, CH_i, located at (x_i, y_i) to the BS placed at $(0, 0)$ as shown in Fig. 5.1. The expected values of $E[D_i]$ and $E[D_i^2]$ are already derived in [2] which are as follows:

$$E[D_i|N = n] = \int_A \frac{1}{A}\sqrt{x_i^2 + y_i^2}dA = 0.765a \tag{5.2}$$

and

$$E[D_i^2|N = n] = \int_A \frac{1}{A}(x_i^2 + y_i^2)dA = \frac{2}{3}a^2 \tag{5.3}$$

As inter-cluster communication experiences d^4 power loss, we also need to know the expected value of $E[D_i^4]$ which is calculated as follows:

$$E[D_i^4|N = n] = \int_A \frac{1}{A}(x_i^2 + y_i^2)^2dA = 0.6222a^4 \tag{5.4}$$

As mentioned before, we consider only multi-hop communication among CHs and between a CH and the BS, where the radio range of CHs should be at least two or more cluster diameters. This means, for cluster radius r_c, the radio range will be $R = 4r_c$ assuming all nodes have an equal level of transmission power. Therefore, the average distance between a CH and the BS is about $h = \lceil D_i/4r_c \rceil$.

A non-CH node communicates with its respective CH at its particular TDMA time slot. Usually, both nodes reside in close proximity within a cluster. Thus, intra-cluster communication experiences negligible data loss. On the other hand, inter-cluster communication spans larger distances compared to intra-cluster communication. Moreover, adjacent clusters' transmission interference, environmental noise and so on, significantly affect the inter-cluster link quality. Inter-cluster communication link quality differs from one link to another. However, for the simplicity of the analysis, we consider L be the link quality of any inter-cluster communication link, measured in terms of packet loss ratio (PLR), as has been described in Section 4.2.2. Let D_i be the distance between a CH node and the BS and m times re-transmission takes place for the lost packet. Since the BS has sufficient energy, we do not consider energy consumed for its reception. Thus, the energy consumed by a CH due to multi-hop communication is as follows:

$$\begin{aligned}
E \quad & [C_{inter(1)}|N=n] = E[(h \times transmission \\
& +(h-1) \times reception + h \times m \times re - transmission \\
& +(h-1) \times m \times re - reception)] \\
= \quad & E[h.e_{TX}(l, D_i/h) + (h-1).e_{RX}(l) \\
& +h.e_{Re-TX}(l, m, D_i/h) \\
& +(h-1).e_{Re-RX}(l, m)|N=n] \\
= \quad & hle_{elec} + \frac{(l\varepsilon_{mp}E[D_i^4|N=n])}{h} + (h-1)le_{elec} \\
& +he_{elec}l\sum_{i=1}^{m} L^i + \frac{(l\varepsilon_{mp}E[D_i^4|N=n])}{h} l \sum_{i=1}^{m} L^i \\
& +(h-1)e_{elec}l\sum_{i=1}^{m} L^i \\
= \quad & (1+\sum_{i=1}^{m} L^i)(0.765e_{elec}la\sqrt{\sigma p} - e_{elec}l + \frac{1.627a^3\varepsilon_{mp}l}{\sqrt{\sigma p}})
\end{aligned} \tag{5.5}$$

Energy consumption at all CH nodes is

$$E[C_{inter}|N=n] = npE[C_{inter(1)}|N=n] \tag{5.6}$$

Total energy spent in the system is

$$\begin{aligned}
E \quad & [C_{total(1)}|N=n] \\
= \quad & E[C_{intra}|N=n] + E[C_{inter}|N=n] \\
= \quad & 2ne_{elec}l - 2npe_{elec}l + \frac{n\varepsilon_{fs}l(1-p)}{\pi\sigma p} + (1+\sum_{i=1}^{m} L^i) \\
& (0.765le_{elec}anp^{3/2}\sigma^{1/2} - e_{elec}lnp \\
& +1.627a^3\varepsilon_{mp}lnp^{1/2}\sigma^{-1/2})
\end{aligned} \tag{5.7}$$

and

$$\begin{aligned}
E & \quad [C_{total}] \\
= & \quad E[N][E[C_{total(1)}|N=n]] = \sigma A.E[C|N=n] \\
= & \quad 2\sigma a^2 ne_{elec}l - 2\sigma a^2 npe_{elec}l + a^2 n\varepsilon_{fs}l\pi^{-1}p^{-1} \\
& \quad -a^2 n\varepsilon_{fs}l\pi^{-1} + (1+\sum_{i=1}^{m} L^i)(0.765le_{elec}a^3np^{3/2}\sigma^{3/2} \\
& \quad -e_{elec}lnp\sigma a^2 + 1.627a^5\sigma^{1/2}\varepsilon_{mp}lnp^{1/2})
\end{aligned} \tag{5.8}$$

Minimizing $E[C_{total}]$ by a value of p,

$$\begin{aligned}
&-2\sigma a^2 ne_{elec}l - a^2 n\varepsilon_{fs}l\pi^{-1}p^{-2} + (1.148le_{elec}a^3np^{1/2}\sigma^{3/2} \\
&-e_{elec}ln\sigma a^2 + 0.8135a^5\sigma^{1/2}\varepsilon_{mp}lnp^{-1/2})(1+\sum_{i=1}^{m} L^i) = 0
\end{aligned} \tag{5.9}$$

Eq (5.9) can be further minimized by multiplying by πp^2 and dividing by lna^2:

$$\begin{aligned}
&1.148e_{elec}a\pi p^{5/2}\sigma^{3/2}(1+\sum_{i=1}^{m} L^i) - \pi\sigma e_{elec}(3+\sum_{i=1}^{m} L^i)p^2 \\
&+0.8135a^3\sigma^{1/2}\varepsilon_{mp}p^{3/2}(1+\sum_{i=1}^{m} L^i) - \varepsilon_{fs} = 0
\end{aligned} \tag{5.10}$$

We assume $x = p^{1/2}$. Since $p\epsilon[0,1]$, $x\epsilon[0,1]$, therefore,

$$\begin{aligned}
f(x) = &\ 1.148e_{elec}a\pi\sigma^{3/2}(1+\sum_{i=1}^{m} L^i)x^5 - \pi\sigma e_{elec}(3+ \\
&\sum_{i=1}^{m} L^i)x^4 + 0.8135a^3\sigma^{1/2}\varepsilon_{mp}(1+\sum_{i=1}^{m} L^i)x^3 - \varepsilon_{fs}
\end{aligned} \tag{5.11}$$

$$\begin{aligned}
f^{'}(x) = &\ 5.74e_{elec}a\pi\sigma^{3/2}(1+\sum_{i=1}^{m} L^i)x^4 - 4\pi\sigma e_{elec}(3+ \\
&\sum_{i=1}^{m} L^i)x^3 + 2.441a^3\sigma^{1/2}\varepsilon_{mp}(1+\sum_{i=1}^{m} L^i)x^2
\end{aligned} \tag{5.12}$$

$$\begin{aligned}
f^{''}(x) = &\ 22.96e_{elec}a\pi\sigma^{3/2}(1+\sum_{i=1}^{m} L^i)x^3 - 12\pi\sigma e_{elec}(3+ \\
&\sum_{i=1}^{m} L^i)x^2 + 4.882a^3\sigma^{1/2}\varepsilon_{mp}(1+\sum_{i=1}^{m} L^i)x
\end{aligned} \tag{5.13}$$

All of $f(x)$, $f^{'}(x)$, and $f^{''}(x)$ are continuous in the whole real domain. We can assume that there is a solution $k\epsilon[0,1]$, where $f(k) = 0$. According to the Newton-Raphson theorem, if $f^{'}(k) \neq 0$, there exists a $\delta > 0$ such that the sequence $\{k_j\}_{j=0}^{\infty}$

defined by (5.14) converges to k for any initial approximation $k_0 \epsilon [k - \delta, k + \delta]$. The iterative algorithm of Newtons method is shown in Algorithm 5.1.

$$k_{j+1} = k_j - \frac{f(k_j)}{f'(k_j)} \quad for\ j = 0, 1, 2, ... \tag{5.14}$$

Algorithm 5.1 Iterative Algorithm

$x \leftarrow 0.1$
$x_1 \leftarrow 0$
$k \leftarrow 0.0000001$
while $(1 > 0)$ **do**
    Calculate $f(x)$
    Calculate $f^{'}(x)$
    $x_1 \leftarrow x - \frac{f(x)}{f'(x)}$
    if $|(x_1 - x)| < k)$ **then**
        $Solution\ \ found$
        Break;
    end if
    $x \leftarrow x_1$
end while
$p \leftarrow x_1 * x_1$

Thus, using Newton-Raphson's theorem, presented in (5.14), we get the approximate value of x as x_{j+1}, and the approximate optimal value of CH selection probability $p_{op} = x_{j+1}^2$ for a reliable and energy efficient WSN. Table 5.1 lists the optimal probability values (p_{op}) achieved numerically using Algorithm 5.1 for the network with n=100, 200, 300 and 400 sensor nodes. In the next section, we will verify these theoretical optimal values with their simulated values.

Table 5.1: The optimal CH selection probability for a multi-hop clustered network

Number of Nodes (n)	**Node Density (σ)**	**Probability (p_{op})**
100	0.0025	0.079
200	0.0050	0.056
300	0.0075	0.045
400	0.0100	0.039

5.1.3 Simulation Results and Performance

The optimal cluster number has a significant effect on network lifetime and reliable data transfer. In this section we will justify the optimal cluster number derived numerically in Section 5.1.2 for a reliable and energy efficient clustered network with the result obtained via simulation.

5.1.3.1 Simulation Model and Environments

We have already used TOSSIM on TinyOS to simulate our models and HEED in the previous chapters. In similar way, we also simulate our proposed optimal cluster number determination technique using TOSSIM.

In our simulation, we use WSN with n=100, 200, 300 and 400 sensor nodes, which are uniformly distributed over a $200m \times 200m$ area. The lossy radio model is considered instead of a lossless medium to simulate a realistic and practical wireless link. We experimented with a range of probability values to find the optimal number of clusters in a wireless sensor system. The Data Loss Ratio (DLR) has been taken into consideration to interpret the effect of a poor inter-cluster communication path. We intend to find the optimal cluster head probability at which this loss is minimal, ensuring reliability and optimizing the energy consumption of the overall system at the same time. We use the same values for the simulation parameters as mentioned in Table 3.2 of Chapter 3.

5.1.3.2 Energy Measure

First, we estimate the energy consumption in the network for a single round of clustering operations with a different CH selection probability. Simulation results as shown in Fig. 5.2 interpret the optimal p_{op} value for WSN with n=100, 200, 300 and 400 of nodes. According to Fig. 5.2, the minimum overall energy consumption has been achieved at the p values of 0.065, 0.06, 0.055, and 0.05 for WSNs with 100, 200, 300 and 400 sensor nodes respectively. The minimum p value closely matches the analytical value for the WSN with 200 and 300 nodes. However, the p value differs a bit from the analytical value for the WSN with 100 and 400 nodes. This deviation is due to the fundamental differences between the numerical solution proposed in this paper and the bedrock of the HEED clustering algorithm, where inter-cluster communication cost

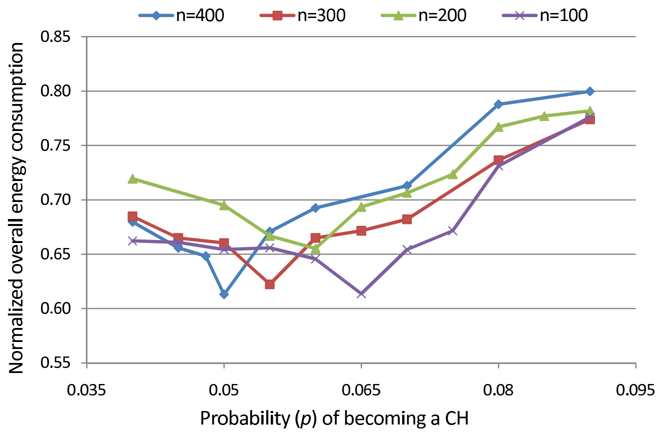

Figure 5.2: Probability of becoming a cluster head

has not been considered at all. The minimum energy consumption takes place at the optimum p value. However, energy consumption increases as the value of p increases or decreases from the optimum value. The p values that are less than the optimal value indicate that fewer nodes are selected as the CH node in the network. As a result the inter-cluster communication distances increase, which again increase the energy consumption according to (2.5). On the other hand, p values with more than the optimal value interpret more CH nodes in the network. Due to this, inter-cluster traffic compared to intra-cluster traffic increases, causing more energy consumption. As shown in Fig. 5.2, the optimal probability of becoming a CH increases as the density of the network decreases.

5.1.3.3 Reliability Measure

Next, we calculate the DLR of the network for a different CH probability using the HEED clustering algorithm and for 100, 200, 300 and 400 sensor nodes using (3.6), defined in Section 3.5.

Figs. 5.3, 5.4, 5.5 and 5.6 show the DLR for WSNs with 100, 200, 300 and 400 sensor nodes respectively. The DLR reading for each of these WSNs has been taken for different CH probabilities. According to Fig. 5.3, the network with 100 nodes shows a maximum drop of DLR at the CH probability value, $p = 0.075$, which is close to the numerical value 0.079, as shown in Table 5.1. Again, as shown in Fig. 5.4, the minimum DLR reading has been obtained at $p = 0.055$, which is almost the same as

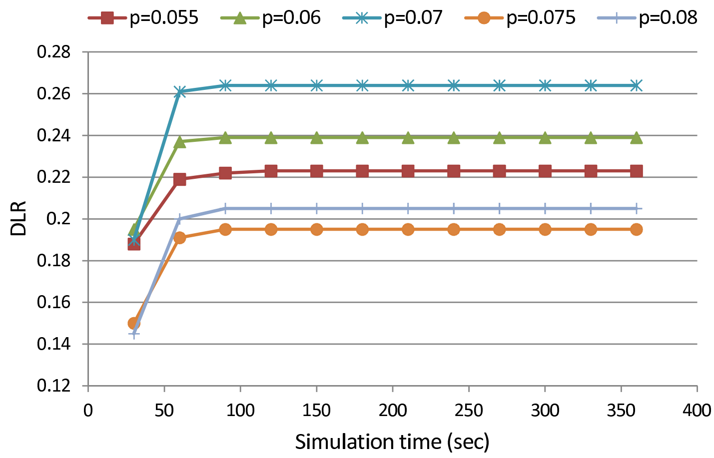

Figure 5.3: Data Loss Ratio (DLR) using 100 nodes

the theoretical value (0.056) for the network with 200 nodes. The minimum DLR, as shown in Fig. 5.5, occurs at $p = 0.045$ for the network with 300 nodes, which is exactly the same that which is derived theoretically. In the case of the network with 400 nodes, as shown in Fig. 5.6, both at $p = 0.04$ and $p = 0.045$, the DLRs exhibit their minimum values, which again affirms the analytical value (0.039). The reason for achieving reduced data loss for a particular p is that p has a direct impact on data loss due to inter-cluster communication. For a given number of nodes in a network, if the value of p is lower than the optimal value, this will increase the inter-cluster distance and eventually increase data loss. Again if the value of p is higher than the optimal value, this will increase the inter-cluster communication traffic in the network, resulting in signal interference and data loss. The above results show that, at a given node density, minimum data loss can be ensured by maintaining an optimal cluster number in the network.

We performed a *t-test* for the pair-wise selected data (pairs were formed with p_{op}) to test the significance of difference in the obtained results of the DLR (Figs. 5.3, 5.4, 5.5 and 5.6). On each occation we take the data at optimal probability and data with other probability values at a 95% confidence level. For 100 nodes with $p_{op} = 0.075$, the *t-test* yielded p-values of 1.6×10^{-12}, 6.1×10^{-22}, 1.7×10^{-11} and 2.3×10^{-5} for p= 0.055, 0.06, 0.07, and 0.08 respectively, asserting that all are significantly different. Again, for 200 nodes with $p_{op} = 0.055$, the *t-test* yielded p-values of 3.4×10^{-13},

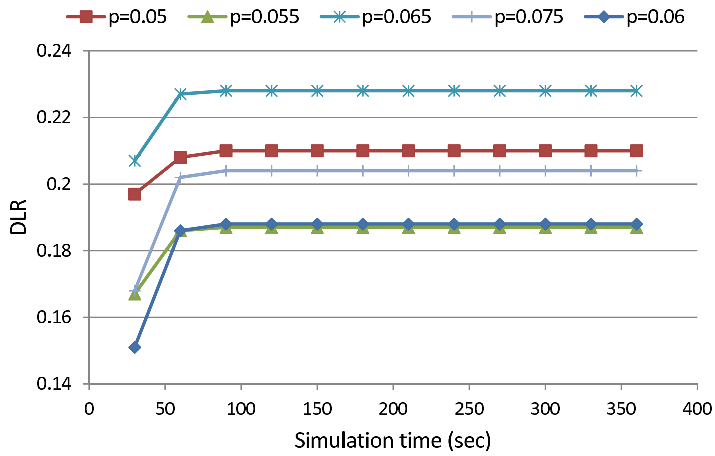

Figure 5.4: Data Loss Ratio (DLR) using 200 nodes

7.2×10^{-1}, 3.1×10^{-25} and 1.4×10^{-7} for $p=$ 0.05, 0.06, 0.065, and 0.075 respectively. It is noticeable that little difference is found between $p_{op} = 0.055$, and $p = 0.06$. This is because they are very close to their analytically derived optimum value of 0.056. For 300 nodes with $p_{op} = 0.045$, the *t-test* yielded p-values of 3.7×10^{-5}, 4.1×10^{-3}, 1.3×10^{-6} and 6.4×10^{-4} for $p=$ 0.05, 0.055, 0.06, and 0.065, respectively, asserting that significantly different. Finally, for 400 nodes with $p_{op} = 0.045$, the *t-test* yielded p-values of 2.8×10^{-1}, 5.3×10^{-2}, 8.4×10^{-3} and 2.2×10^{-2} for $p=$ 0.04, 0.05, 0.055 and 0.06 respectively. In this case, little difference has been found between $p_{op} = 0.045$ and $p_{op} = 0.04$, which is also close to our theoretical result (0.039). In most cases, there are significant differences in terms of reliability values; however, there are some cases where the differences are not significant. This is because the probability values for optimal cluster head selection are very close to their respective theoretical values. Thus, we find that the simulation results presented in Fig. 5.2, 5.3, 5.4, 5.5 and 5.6 comply with the theoretically obtained results shown in Table 5.1.

As mentioned at the beginning of this chapter, determination of the optimal cluster number without considering the deployment environment does not provide the efficacy of a full optimization technique and, therefore, requires the joint optimization of the cluster number and their organization. We will present the strategy of this joint optimization technique in the following section.

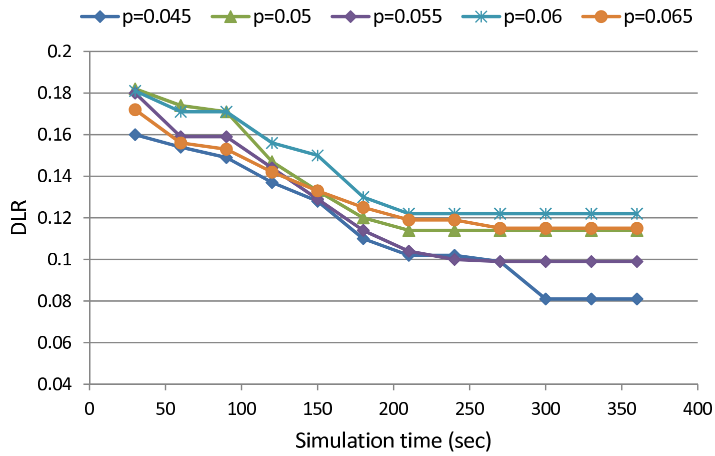

Figure 5.5: Data Loss Ratio (DLR) using 300 nodes

5.2 Joint Optimization of Number and Allocation of Clusters

5.2.1 System Model

The system model described in Section 5.1.1 is the same as the model required for this technique. As the BS has unlimited energy supply, and it already knows the basic parameters of the deployed sensor nodes, we can leave the determination process of the optimal cluster number to the BS. This shifts the distributed clustering approach to a hybrid of centralized and distributed approaches and also delegates the responsibility amongst the BS and sensor nodes. This process has been articulated in the next section, which is an important part of the overall network clustering process.

5.2.2 Cluster Formation Process

5.2.2.1 CH selection process

The first step in JOC is to build a hierarchal neighbourhood structure of all the sensor nodes and BS, based on a particular transmission range of sensor nodes. This hierarchal structure formation starts from the BS whose level is 0, and nodes are distributed in different levels based on their neighbourhood relationship, as shown in Fig. 5.7. As the neighbour has been calculated considering only the transmission range, the neighbours of one node may overlap with the neighbours of other nodes in the same level; i.e.

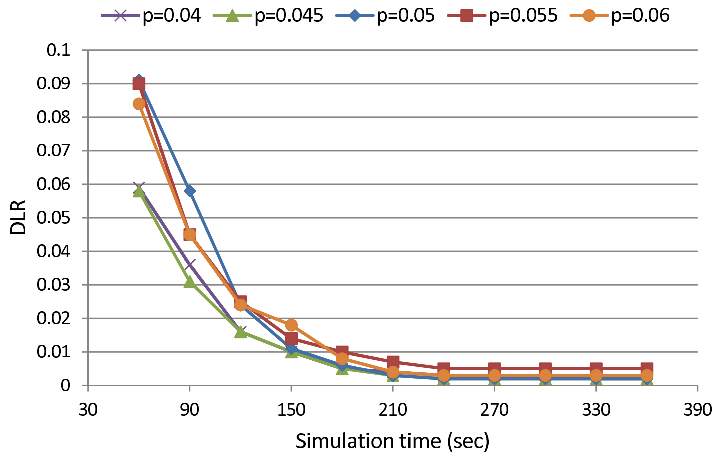

Figure 5.6: Data Loss Ratio (DLR) using 400 nodes

neighbours are not mutually exclusive.

According to Fig. 5.7, A, B and C are closest to BS and denoted as level-1 CH nodes, whereas D, E and F are level-2 CH nodes based on their position. The transmission ranges of CH nodes A and B overlap and, therefore, 2 member nodes, marked by a grey colour, fall into this overlapped region. In the same way, due to the overlapping of transmission ranges, B also shares 2 nodes with C in the same level and 1 node with D at the next level.

The cluster formation process depends on the following important parameters:

1. N_{non} is the number of non-overlapping neighbouring nodes of a particular node. The higher the number of N_{non}, the higher the chance of a node becoming a CH.

2. E_{RE} is the residual energy of a node, the higher value of which also increases the chance of a node becoming a CH.

3. ARE is defined as the average reachable energy required by all member nodes within the cluster range of a node if it is selected as a CH; i.e.

$$ARE = \frac{\sum_{j=1}^{C_i} E_{intra}(j)}{C_i}$$

where, C_i is the number of member nodes within the cluster, CH_i, $E_{intra}(j)$ is the energy required by j^{th} member node to transmit the data to its CH node. The value of ARE dictates the position of a CH node in a cluster. The minimum

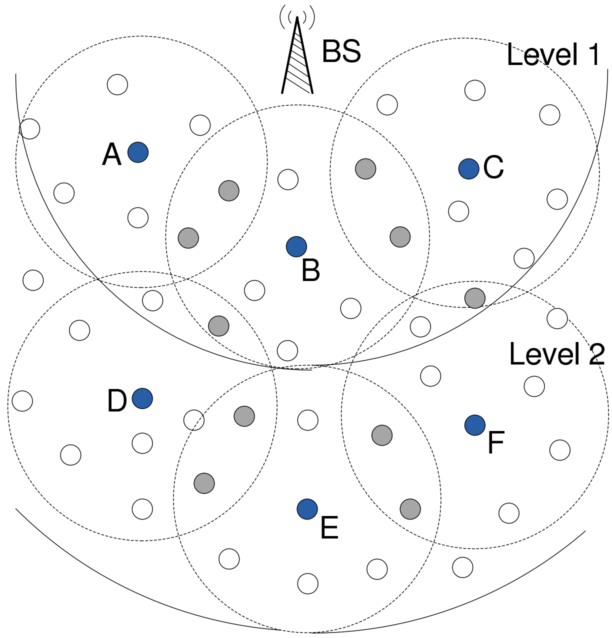

Figure 5.7: Cluster formation: (a) blue nodes are CH nodes, (b) white nodes are CH member nodes and (c) grey nodes are overlapping nodes.

the ARE, the better the chance a CH node will be placed at the center of a cluster.

Therefore we deduce the following equation depending on which node would be selected as a CH and also drive the CH selection process progressively from the BS to the far end of the network:

$$U = \begin{cases} \infty & if\ N_{non} > N^{'}; \\ \frac{N}{1+N_{non}}[\frac{E_{max}}{E_{RE}}(1+\frac{ARE}{ARE_{max}})] & otherwise \end{cases} \quad (5.15)$$

To control the distribution of nodes amongst the clusters, we intuitively defined the upper bound for the degree of a node, which is denoted by $N^{'}$. According to (5.15), a node with minimum U in a neighbourhood needs to be selected as a CH node.

The inclusion of ARE in the above equation will reduce the chance of having a CH away from the center of that cluster due to the consideration of the remaining energy. Minimization of the function described in (5.15) will reduce the likelihood of a CH suddenly breaking down and thus improve both reliability and energy consumption.

Now we will present the steps to be followed by all nodes for clustering the whole network. At this stage, we consider that all nodes are set at a particular transmission range.

1. Initialization phase:

   (a) All nodes develop their neighouring table with the list of neighouring node IDs and their respective information, such as E_{RE}, ARE and node status (Overlapping/Non-overlapping node) using the specified values of intra and inter-cluster transmission ranges.

2. CH selection phase:

   (a) This begins with a node of a particular level (at the very beginning from the first level) and calculates its U value based on (5.15).

   (b) The node with minimum U value is declared as a CH.

   (c) This CH selection process continues for all other nodes of the same level that have not been either declared as CH or assigned as a member to a particular CH.

   (d) When the CH selection process of all nodes in that level is complete, then the same process articulated in steps 2a - 2c continues for all next levels.

3. Finalization phase:

   (a) After the completion of the CH selection process, if a node still has not become a CH or CH member node, then it will declare itself as a CH.

For example, adopting the above steps, we modeled the hierarchical structure of clusters for using Matlab, as is shown in Fig. 5.8. Here we used 200 nodes spread across an $200m \times 200m$ area, where the intra and inter-cluster transmission ranges are taken as $20m$ and $40m$ respectively. The number of CH nodes selected in this case is 34. If the intra and inter-cluster transmission ranges are increased, i.e. from 20 and 40 to 30 and 60, the number of CHs become 26, as shown in Fig. 5.9. Black stars and red squares of Fig. 5.8 and Fig. 5.9 represent member nodes and CH nodes respectively, while the big green square symbol represents the BS. Blue circles represent the transmission range of respective CHs and the blue straight lines represent the intra-cluster communication.

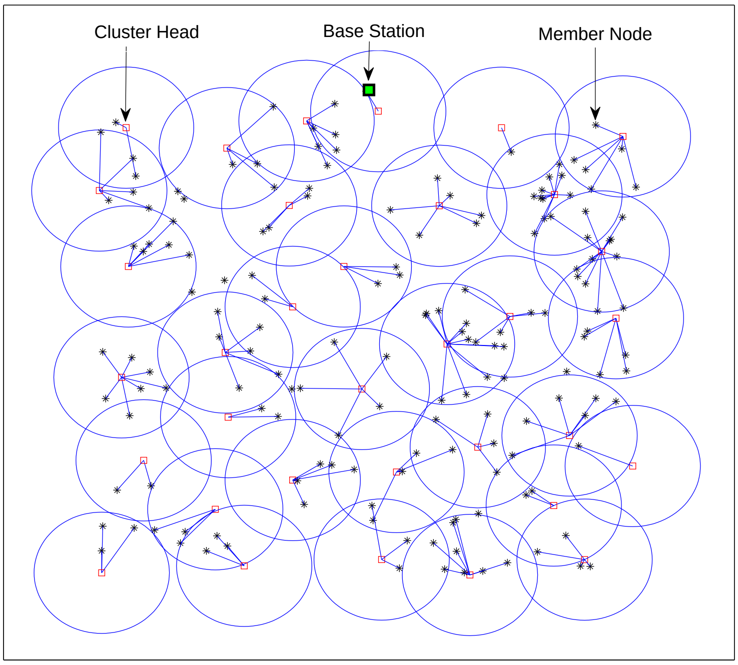

Figure 5.8: Clustering with a sample network of 200 nodes and for intra and inter-cluster transmission ranges $20m$ and $40m$, respectively.

5.2.2.2 Estimation of Intra and Inter-Cluster Energy Consumption

CH consumes most of the energy in a cluster. The energy consumption of each CH consists of two parts: (i) intra-cluster and (ii) inter-cluster communication. Inter-cluster communication also takes place in two ways: i.e. forwarding its own cluster's aggregated data to the next CH and relaying data from one CH, to another CH, or to the BS.

As intra-cluster communication takes place within a short distance, most of the time link quality remains good. Furthermore, member nodes transmit data to the respective CH in a TDMA fashion, Hence, signal interference due to intra-cluster communication is negligible. For this reason, we ignore packet loss for intra-cluster communication. On the other hand, as mentioned before, inter-cluster communication takes place in longer distances, therefore it suffers from packet loss due to poor link quality between source and destination CHs. Packet loss also occurs due to traffic congestion at the destination CH node and sudden break down of a CH node. The reliability of the entire network is determined by the packet loss ratio (PLR). When packet loss occurs, the CH demands

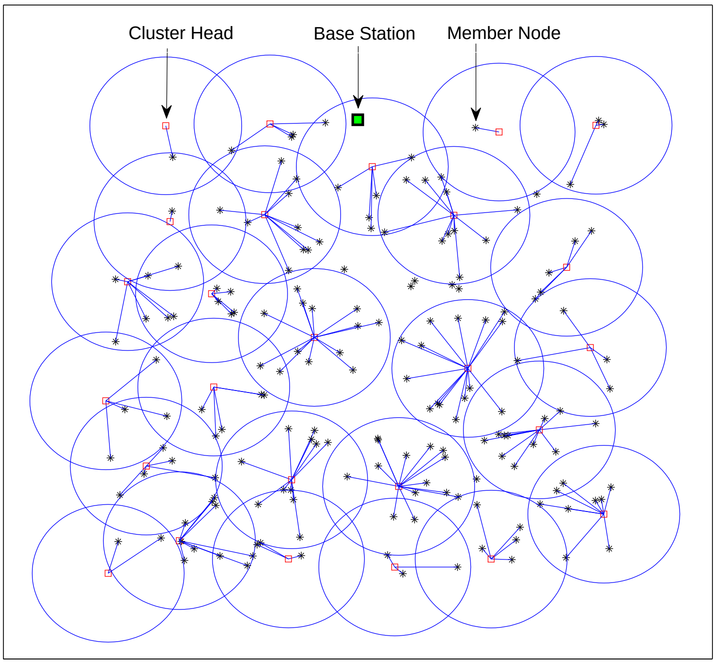

Figure 5.9: Clustering with a sample network of 200 nodes and for intra and inter-cluster transmission ranges $30m$ and $60m$, respectively.

re-transmission of the lost packet, which in turn demands extra energy consumption. Therefore, for improving the reliability of the network we need to consider the required re-transmission of lost packets in calculating the inter-cluster communication cost.

We follow the same energy model as defined in (2.4), (2.5) and (2.6) to define the intra-cluster energy consumption function for i^{th} cluster as

$$\begin{aligned} & E(C_i|r_{intra}) \\ = \; & C_i \times E_{tras}(r_{intra}) + C_i \times E_{recv} + C_i \times E_{da} \\ = \; & C_i \times (le_{elec} + l\varepsilon_{fs} r_{intra}^2) + C_i \times le_{elec} \\ & + C_i \times l \times E_{da} \end{aligned} \tag{5.16}$$

where, C_i is the number of member nodes in i^{th} cluster. We also define the inter-cluster energy consumption function for the transmission link between CH_i and CH_j

as:

$$\begin{aligned}
& E(C_{ij}|r_{inter}, m, L_{i,j}, B_{i,j}) \\
= \; & (C_{ij} \times E_{recv} + (C_{ij}+1) \times E_{tras}(r_{inter})) + (C_{ij} \times \\
& E_{recv} + (C_{ij}+1) \times E_{tras}(r_{inter})) \sum_{s=1}^{m} (L_{ij}^{s} + B_{ij}^{s}) \\
= \; & (C_{ij} \times le_{elec} + (C_{ij}+1) \times (le_{elec} + l\varepsilon_{mp} r_{inter}^{4})) + (C_{ij} \times \\
& le_{elec} + (C_{ij}+1) \times (le_{elec} + l\varepsilon_{mp} r_{inter}^{4})) \sum_{s=1}^{m} (L_{ij}^{s} + B_{ij}^{s})
\end{aligned} \tag{5.17}$$

where, C_{ij} is the number of multi-hop traffic relayed by CH_i node in a round, m is the number of packet re-transmission and for l-bit message transmission by each node. Also, L_{ij} is the link quality between two CHs: CH_i and CH_j. B_{ij} indicates packet loss due to congestion at the destination CH node, CH_j, while transmitted from CH_i. Both L_{ij} and B_{ij} are expressed in terms of packet loss ratio.

5.2.2.3 Formation of the Spanning Tree

As inter-cluster communication takes place on the CH overlay, we need to construct the suitable spanning tree so that a aggregated message from a CH node reaches to the BS through the best path; i.e. the path that requires the lowest transmission energy, including the energy required for the number of re-transmissions for the poor link quality and high traffic congestion. A detailed calculation of the best path has been presented in Chapter 4.

If the number of cluster members, C_i, increases, the signal interference and the chance of packet drop due to congestion at CH node also increases. The same is true for C_{ij}, which interprets the quantity of multi-hop traffic. Every packet drop requires re-transmission of the packet, which inevitably increases energy consumption. Therefore, based on (5.17), a CH node for forwarding packet towards BS could be selected, minimizing the energy cost in obtaining reduce data loss and energy consumption. The following steps are followed in the inter-cluster tree construction phase:

1. The tree generation process initiates from the highest (bottom) level CH nodes. As every CH node maintains a neighbouring node table, a CH node may find one or more CH nodes within its inter-cluster transmission range.

2. A CH node then finds its best forwarding CH node towards the BS whose inter-cluster communication cost calculated by (5.17) is at a minimum.

3. Steps 1 and 2 continue for all CH nodes for all levels or until the BS is reached.

An example of the inter-cluster spanning tree produced using the cluster organization shown in Fig. 5.8 is presented in Fig. 5.10.

Again, red squares represent member nodes and CH nodes and big green squares represent the BS. Blue circles represent the transmission range of respective CHs. The blue straight lines represent the inter-cluster communication. This figure shows that the routing tree constructed by our optimal clustering technique produces a fully a connected tree. The calculated routing path, represented as a minimum spanning tree, is shown as connected CHs and BS with solid lines in Fig. 5.10. The overall energy consumption for the entire network for a single network operation round can be estimated, dependent on intra and inter-cluster transmission ranges, link quality and traffic congestion. However, it has been proved that to maintain the connectivity of the entire network, inter-cluster transmission range is $r_{inter} \geq 6 \times r_{intra}$ [14]. Since we know the lower bound of r_{inter} in terms of r_{intra}, we can intuitively determine the suitable value of r_{inter} using a particular value of r_{intra}. As the link quality and congestion varies with time and are estimated during the network operational time, the overall energy consumption of the entire network can be represented as a function of r_{intra} using (5.16) and (5.17):

$$E(r_{intra}) = \sum_{i=1}^{q} E(C_i|r_{intra}) + \sum_{(i,j)\epsilon D}^{|D|} E(C_{ij}|r_{inter}) \tag{5.18}$$

where, q is the total number of clusters in the network and D is the set of all edges for the inter-cluster communication path (routing) contained in the spanning tree, as shown in Fig. 5.10 between two CH nodes (CH_i, CH_j) and CH_i to BS.

For a better understanding of the formation of the spanning tree, the process can be explained further by using a simplified version of Fig. 5.10, as shown in Fig. 5.11. The inter-cluster tree construction phase is basically a distributed formation of a Breadth-First-Search (BFS) tree rooted at the BS, as illustrated in Fig. 5.11. The tree construction starts from the BS with leveling CH nodes, and is carried out based on the

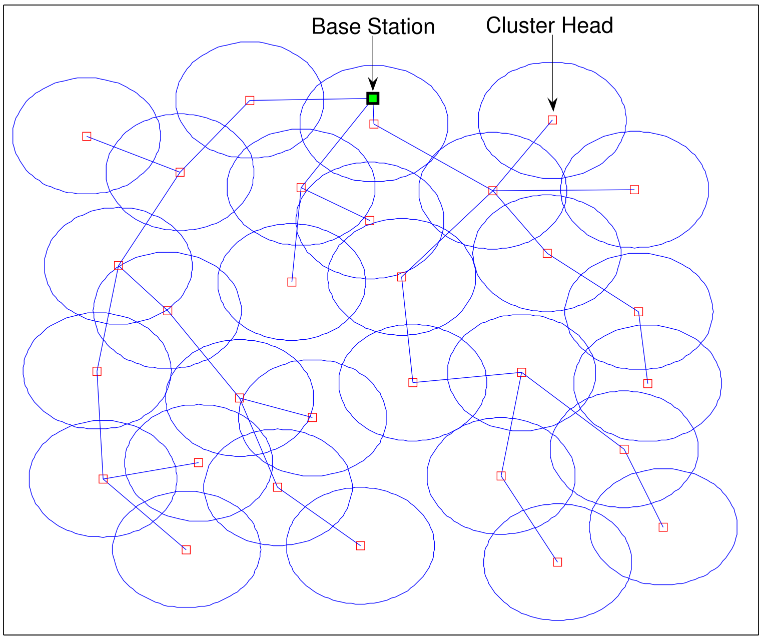

Figure 5.10: Inter-cluster communication tree with a sample network of 200 nodes.

position of CH nodes. In this case (Fig. 5.11(a)), A, B and C are leveled as level-1 CH nodes and D, E F, and G are level-2 CH nodes.

Table 5.2: Inter-cluster communication (a) possible communication link and (b) final communication tree structure.

	A	**B**	**C**	**D**	**E**	**F**	**G**
(a)	BS,B	BS,A,C,D	BS,B	A,B	A,B,D	B,C	B,C
	D,E	E,F,G	F,G	E	F,G	E,G	E,F
(b)	BS	BS	BS	A	B	G	C

Each CH node maintains its neighbouring CH list together with their respective level information, which is summarized in Table 5.2. Using this list, A, B and C select BS as their parent, as they are close to the BS. However, D has 3 options (A, B, and E); of these, A and B are one level closer to the BS than E. Therefore, D selects either A or B as its parent node. This decision is taken by using the communication cost calculated by (5.17), which depends on both link quality and congestion factors. Thus, in this case, D finally selects A as its parent. Other CH nodes also select their parent nodes in the same way and finally construct a inter-cluster communication tree

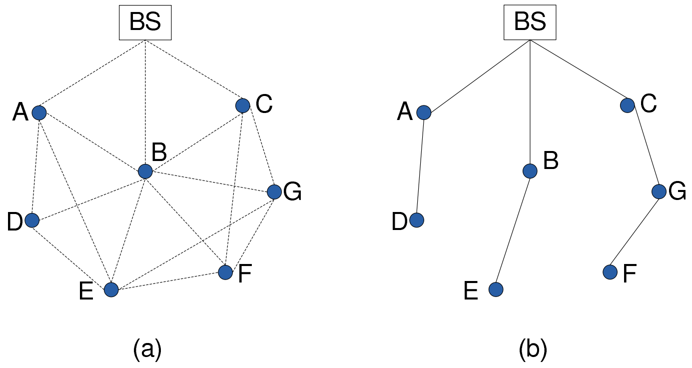

Figure 5.11: (a) Possible inter-cluster communication links and (b) constructed spanning tree.

as shown in Fig. 5.11(b).

5.2.2.4 Determination of Optimum Transmission Range

The number of CHs decreases exponentially with the increase of the intra-cluster transmission range, (r_{intra}) [14]. The reliability and energy consumption of the whole network also depends on r_{intra}. Therefore, joint optimization of cluster number determination and clustering technique can be achieved by optimizing (5.18) with respect to r_{intra}, whose objective function can be formulated as:

$$\begin{aligned} find \quad & r_{intra} \\ subject\ to \quad & r_{intra} = \arg\min(E(intra)) \end{aligned} \tag{5.19}$$

The results in Fig. 5.12 show that energy minimization converges to only a particular transmission range for a network with 200, 300 and 400 sensor nodes. They also show that the energy consumption for a given network varies with the transmission range and follows a convex path. For smaller values of r_{intra}, the intra-cluster communication cost is less. However, the number of clusters becomes higher and hence the inter-cluster communication cost increases. Thus, the overall communication cost increases. On the other hand, for higher values of r_{intra}, a fewer number of CH nodes are selected. In this case, both the intra and inter-cluster communication cost increases because of the required longer transmission ranges, which yields an overall higher energy consumption. This indicates that there exists a minimum value of (5.18). For example, from the results it is shown that for a network with 200, 300 and 400 sensor nodes, the values of r_{intra} for the minimum of (5.18) are 18, 18 and 19 respectively.

Since energy consumption versus r_{intra} is a convex curve, any optimization technique can be used to find the r_{intra} using (5.18). In this project, we have used a gradient descent algorithm to find the r_{intra}, whose pseudo-code is provided in Algorithm 5.2.

Algorithm 5.2 Determine Optimum Transmission Range

$n \leftarrow$ Total number of nodes
$E_{max} \leftarrow$ Maximum energy of a node
$Step \leftarrow 1$
$\Delta \leftarrow 0.01$
$r_{intra} \leftarrow 10$
$r_{intra\_old} \leftarrow 0$
$E\_tot\_old \leftarrow n * E_{max}$
while $|r_{intra} - r_{intra\_old}| > \Delta$ **do**
    Clustering steps 1a - 3a of Section 5.2.2
    Tree formation steps 1 - 3 of Section 5.2.2.3
    $E\_tot \leftarrow$ Total $(E_{intra} + E_{inter})$ According to (5.16) [For one round]
    $r_{intra\_new} \leftarrow (r_{intra} - Step * \frac{E\_tot - E\_tot\_old}{r_{intra} - r_{intra\_old}})$
    $r_{intra\_old} \leftarrow r_{intra}$
    $r_{intra} \leftarrow r_{intra\_new}$
    $E\_tot\_old \leftarrow E\_tot$
end while
Print "Minimum energy consumption occurs at transmission range:", r_{intra};

After finding r_{intra} using the optimization technique, the network set up using its corresponding minimum spanning tree is performed to make it ready for network operation. Each CH node sends a confirmation message consisting of TDMA time slot information to its respective member nodes. Inter-cluster communication occurs according to the routing path constructed using the minimum spanning tree based on the CSMA protocol.

5.2.3 Simulation Results and Performance

Via simulations, we now evaluate the performance of JOC in terms of data transmission reliability, as well as energy efficiency. We present the performance comparison of the proposed JOC with the popular HEED [14] clustering protocol, which is implemented using TOSSIM (A simulator of TinyOS). TOSSIM is also used to implement JOC.

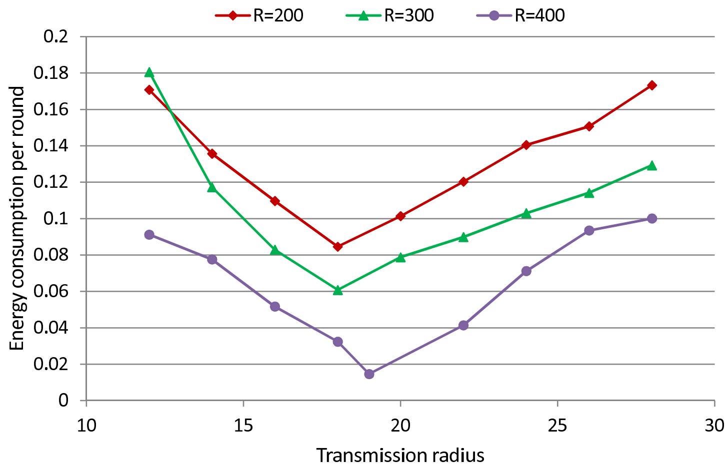

Figure 5.12: Energy consumption at different transmission range for 200, 300 and 400 nodes.

5.2.3.1 Simulation Model and Environments

We simulated a sensor network with 200 nodes deployed non-uniformly over a $200m \times 200m$ area. The lossy radio model is considered to simulate a realistic and more practical link. The initial energy of a sensor node is considered as $0.5J$. A node is considered "dead" if it loses 99% of its initial energy. To get a realistic and practical result we considered an energy model, which includes all energy spent, such as data aggregation, data transmission and reception, multi-hop data forwarding and data re-transmission. For a fair comparison, the network topologies, node distribution, node-energy distribution, channel propagation model and other simulation parameters were kept identical across all protocols. As with [14], the simulation parameters are the same as listed in Table 3.2.

At first, we calculate the lifetime (both the time until the first node dies and the time until the last node dies) of the network using HEED and JOC with transmission ranges R=16, 18, 20, 22 and 24. Then, as a reliability measure, we calculate the DLR of the network for both of the protocols using (3.6).

5.2.3.2 Energy Measure

According to Fig. 5.13, the JOC has achieved a significant lifetime gain in the network as compared to HEED. These increases in lifetime for JOC with transmission ranges

R=16, 18, 20, 22, 24 over HEED were about 27%, 29%, 35%, 29% and 27% for the first node death and about 38%, 47%, 51%, 46% and 40% for the last node death, respectively. The simulation results assert that the lifetime gain has achieved its maximum for $R = 20$, which is deduced as an optimum for the network. Results also indicate that the network lifetime decreases for other R values.

The introduction of the node's remaining energy in the CH selection process reduced the risk of sudden death of a node and balanced the energy expended amongst the nodes. More importantly, blending the ARE factor in the CH selection process helped select a CH at the center of the cluster, which further reduced the energy consumption for each of the clusters. Every packet drop at the time of communication demands re-transmission of that packet, wasting the additional precious energy of a node. By introducing the link quality and traffic congestion factors, we could select the best inter-cluster packet transmission path. As a result, the overall energy utilization has acquired a substantial gain over HEED.

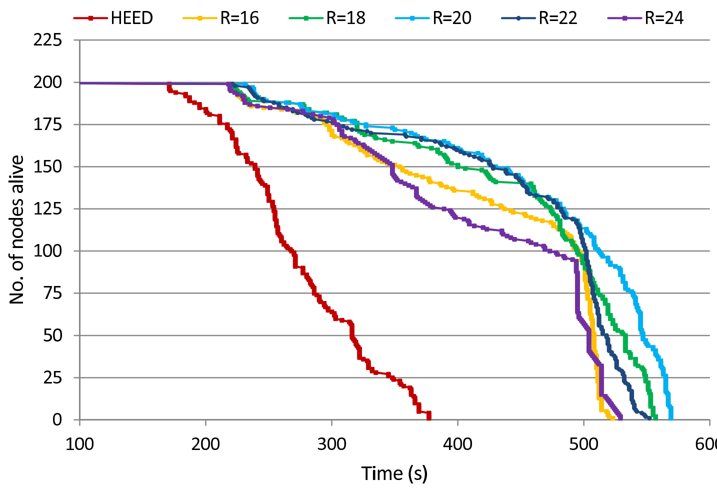

Figure 5.13: Network lifetime for 200 nodes using HEED and Optimal clustering with different transmission ranges.

We can conclude that the proposed JOC has attained a huge lifetime gain over the contemporary clustering protocol. Furthermore, JOC clearly reveals that a node's transmission range or cluster size has a significant impact on energy consumption, optimal selection of which can maximize the energy utilization of any network.

5.2.3.3 Reliability Measure

Fig. 5.14 shows the DLR of HEED and JOC for different transmission ranges. For JOC with transmission ranges R=16, 18, 20, 22 and 24, the DLR drops an average of 4%, 27%, 36%, 20% and 12%, respectively, as compared to HEED. The maximum DLR drop occurs for a JOC with $R = 20$, where it is 27% at the beginning and 45% at the end. This again confirms that when using JOC at $R = 20$ network provides minimum data loss, which indicates the optimum transmission range for the network. The JOC is designed to calculate the node's transmission range at the time of the CH selection process, which also maintains better connectivity amongst the CH nodes by dictating the inter-cluster communication range. Moreover, link quality and traffic congestion factors are taken into account in the inter-cluster tree generation process. For all of these reasons, the JOC can achieve reduced packet loss at the time of inter-cluster communication and can enhance the reliability of the network.

It is noticeable that the optimum transmission range obtained by the simulation results for the JOC does not exactly match the optimum transmission range obtained previously by numerical analysis. There are several reasons for this small variation in the obtained results. When the simulator program executes, it introduces a few other parameters that come from the implementation of other layers. The impact of these parameters can cause a small deviation from the expected results. Thus, the above results imply that the selection of an optimal transmission range or cluster size in the network has a considerable impact on reducing data loss in the network.

The simulation results (Fig. 5.13 and Fig. 5.14) confirm that the JOC improves both reliability and prolongs the network lifetime over other relevant clustering schemes. The JOC obtains an optimum value of r_{intra} within a few iterations of the JOC and cluster the network, which can maximize both data reliability and energy utilization of the network. Even though the JOC can find the best transmission range for utmost performance, it can also find out the quasi-optimal values of r_{intra}, which are very close to the optimal value depending on the value of the step size presented in Algorithm 5.2.

We performed a *t-test* for the pair-wise selected data to test the significance of the difference in the obtained results for both network lifetime (Fig. 5.13) and DLR (Fig. 5.14). Each time we took the data from HEED and data from the JOC with different R values at a 95% confidence level. At first, for a network lifetime using

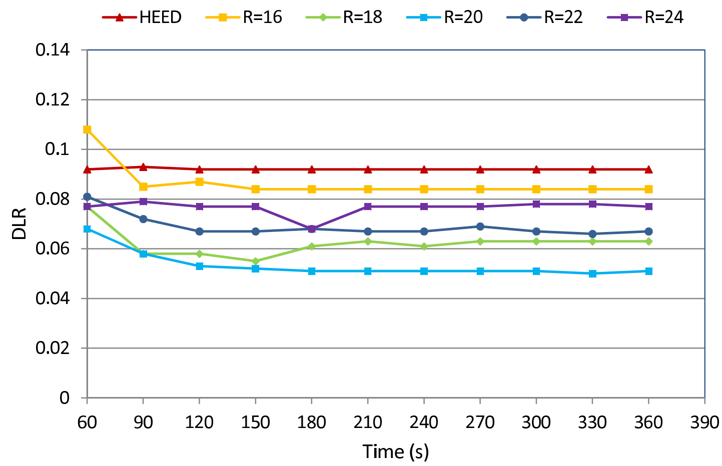

Figure 5.14: Data Loss Ratio for 200 nodes using HEED and Optimal clustering with different transmission ranges.

200 nodes, the *t-test* yielded p-values of 2.7×10^{-95}, 5.7×10^{-114}, 4.2×10^{-117}, 3.7×10^{-113} and 2.8×10^{-99} for $R=$ 16, 18, 20, 22 and 24 respectively, asserting that all are significantly different. Then, for reliability using 200 nodes, the *t-test* yielded p-values of 0.03, 0.0011, 0.00016, 0.002 and 0.02 for $R=$ 16, 18, 20, 22 and 24 respectively, denoting significant differences.

5.3 Summary

Determining the optimal cluster number is an essential step prior to applying the clustering algorithm in WSNs. For increasing the reliability of WSNs, firstly, we have developed the theoretical model in terms of energy cost to achieve an optimal CH selection probability by embedding the link quality in the theory of the CH selection process. The results obtained by intensive simulation of a multi-hop clustering protocol have endorsed our theoretical results. Thus, we have demonstrated that by using different CH selection probability for a WSN, the reliability of the whole network has been significantly improved, while at the same time minimum energy consumption has been maintained. However, the main contribution of this paper is a new clustering protocol (JOC), which jointly minimizes data loss and energy consumption of a WSN. For improving reliability and energy efficiency, we have embedded the link quality, traffic congestion and both the intra and inter-cluster communication cost in the bedrock of the proposed clustering technique. The JOC is suitable for both uniform and non-uniform node distribution and can be applied to any large scale WSN applications that require data reliability and prolonged network lifetime.

As far as we are aware the introduction of this joint optimization of cluster numbers and their organization is the first of its kind. Even though the JOC shows a promising performance in terms of both reliability and network lifetime, and it is expected that it will open an avenue of new research, there are a number of limitations in this approach. These limitations and how they can be addressed will be presented in the next chapter of this research project.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Designing routing protocols for a WSN is challenging as there is no fixed infrastructure in a WSN and sensors are mostly location unaware. Routing protocols for a WSN are of paramount importance as they greatly contribute to overall system scalability, reliability and energy efficiency. However, these performance metrics have not been properly explored in the existing routing techniques. Moreover, due to ignoring time-varying constraints, such as link quality and congestion, the usual routing protocols result in non-optimal reliability and energy consumption.

This thesis has directly addressed the above mentioned issues by introducing a number of cluster-based protocols so that both reliability and energy efficiency can be improved at the same time. Firstly, to deal with a sudden CH breakdown situation in the network, a *backup clustering scheme* is proposed. The proposed backup clustering scheme optimally determines a set of BCHs and their corresponding switching times. This also eliminates the threshold value required for the switching process and automatically derives the switching time. The performance of our backup clustering technique has proven very effective in handling node failure. Additionally, it has enhanced network reliability and lifetime, and reduced the messaging overhead of the network. This technique is capable of performing on top of any suitable clustering technique. However, as the proposed backup clustering technique does not consider the inter-cluster cost in developing the routing path, the proposed backup clustering scheme may not exhibit its utmost performance. This leads us to develop two inter-cluster communication schemes, called the *Multi-hop Route Selection Scheme (MRSS)* and the *optimum route selection* schemes. The *MRSS* and the *optimum route selection* schemes are developed mainly to handle a *hot-spot* problem leading to CH node failure in a WSN. Therefore, instead of considering the shortest path based on minimum hop count for route selection, we have employed techniques based on a cost function. In the cost function, we have incorporated CH nodes' remaining energy, link quality and congestion at a CH node in terms of energy while constructing the routing path. Moreover, the proposed schemes can be seamlessly applied to any clustering algorithm. Based on the performance analysis, it is been shown that both our proposed inter-cluster communication schemes have significantly increased the reliability and energy efficiency of the network at the same time. Although all of our inter-cluster communication schemes increase performance, the problem of the inter-cluster communication cost during the clustering process remains. Moreover, due to decoupling the cluster number determination and the clustering process and handling these two issues separately, the existing clustering techniques failed to attain the desired optimum reliability and energy efficiency.

This has driven us to finally develop a *joint optimal clustering (JOC)* technique, which optimizes both the number of clusters and their organization by considering intra and inter-cluster communication cost, link quality and traffic congestion so that both reliability and energy efficiency are maximized simultaneously. The advantage of JOC is that it is more suitable for non-uniform node distribution.

Based on the simulation results performed for all the proposed algorithms, it is evident that all our developed algorithms have outperformed other contemporary clustering and backup clustering schemes in terms of both reliability and network lifetime. Our backup clustering scheme also successfully handles a sudden node breakdown situation. As solar energy has appeared as a renewable and environment-friendly technology, we conducted another experiment on the backup clustering scheme that considers a portion of nodes to be equipped with solar cells. The results also exhibited a significant gain achieved by the proposed method for both reliability and energy efficiency compared with existing clustering and backup clustering schemes for the same network scenario. Based on the experimental results, it is evident that our efficient inter-cluster routing scheme could achieve improved reliability and energy utilization. Finally, the proposed JOC technique showed a substantial performance gain in terms of reliability and network lifetime over the contemporary and popular clustering techniques. A statistical $t - test$ on the results obtained showed that all of them are significantly different.

6.2 Future Works

The research strategies for achieving both reliability and energy efficiency through effective cluster-based routing protocols presented in this thesis can be further extended in a number of directions, some of which are highlighted below:

- A backup clustering technique has been developed and tested with the HEED clustering protocol. This new backup clustering technique showed a substantial performance gain both in terms of network reliability and energy utilization. It would be very interesting to explore the efficacy of this technique when it is embedded into the bedrock of our proposed joint clustering technique.

- It is an additional job for a CH node to run a separate process to select its BCH. As the selection of CHs and their organization has been done in our proposed technique, a similar technique could be used to select a set of BCHs for a CH considering the inter-cluster communication cost in terms of energy required for transmission and re-transmission due to the packet loss for link quality and traffic congestion. As with our joint clustering technique, it is expected that this also will improve network reliability and lifetime significantly.

- It is also very important to maintain connectivity while a clustering process is applied on the network. Connectivity amongst nodes during intra-cluster communication can be guaranteed, and the lower bound for inter-cluster communication range has been provided for uniform node distribution in [14]. However, in the case of non-uniform node distribution, the inter-cluster communication distance could exceed the selected transmission range of a CH. As a result, a cluster may become isolated from the rest of the network. Therefore it is necessary to determine the suitable value of an inter-cluster communication range that utilizes the dispersion of CHs.

- Dynamic transmission power control improves power consumption up to 16% compared to the fixed transmission-power control [142]. Transmission power level of a typical sensor node is adjustable. Within the framework of cluster-based routing protocols introduced in this thesis, both intra and inter-cluster communication ranges have been considered to be the same at all levels of the hierarchal cluster organization. To fulfill the objective of achieving the optimal values for reliability and energy efficiency of a WSN, both intra and inter-cluster transmission ranges at different levels can be determined considering the distribution of sensor nodes.

- It is also necessary that the proposed technique is environmental friendly and sustainable. Therefore, while developing clustering protocols for a WSN using the above mentioned ideas, performance of these protocols (except the backup clustering technique) should be tested with a sensor node embedded with solar or another renewable energy source. Solving these problems would contribute towards achieving an environmentally friendly world.

Publications from this work

Conference publications:

1. A. Sadat, and G. Karmakar, "Optimum Clusters for Reliable and Energy Efficient Wireless Sensor Networks," in *IEEE International Symposium on Network Computing and Applications* (*NCA*), USA, Aug. 2011.

2. A. Sadat, and G. Karmakar, "Optimal Reliable and Energy Aware Inter-Cluster Communication in Wireless Sensor Networks," in *IEEE Asia-Pacific Conference on Communications* (*APCC*), New Zealand, Nov. 2010, pp. 221–226.

3. A. Sadat, and G. Karmakar, "A Trade-off between Reliability and Energy Efficiency for Inter-Cluster Communication in Wireless Sensor Networks," in *IEEE International Conference on High Performance Computing and Communications* (*HPCC*), Australia, Sep. 2010, pp. 573–578.

4. A. Sadat, G. Karmakar, A. Zaslavsky, and M.M. Gaber"Reliable and Energy Efficient Backup Clustering Scheme for Wireless Sensor Networks," in *International Conference on Information Networking* (*ICOIN*), Korea, 2010, (**Awarded the Best Paper**).

Conference article submitted:

1. A. Sadat, G. Karmakar, and D. Green, "Joint Optimization of Number and Allocation of Clusters for Wireless Sensor Networks," in *IEEE International Conference on Communications* (*ICC*), Canada, June. 2012.

Appendix A

The total energy required to transmit all multi-hop data packets up to the BS following all links of the route r for source CH_i is,

$$
\begin{aligned}
E_{rit}(D) &= Pl_1(e_{elec}+\varepsilon_{mp}d^4_{i,i+1}) + Pl_1(e_{elec}+\varepsilon_{mp}d^4_{i,i+1})\sum_{s=1}^{m}(L^s_{r,i,i+1}+B^s_{r,i,i+1}) \\
&+ Pl_1(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(e_{elec}+\varepsilon_{mp}d^4_{i+1,i+2}) \\
&+ Pl_1(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(e_{elec}+\varepsilon_{mp}d^4_{i+1,i+2})\sum_{s=1}^{m}(L^s_{r,i+1,i+2}+B^s_{r,i+1,i+2}) \\
&+ Pl_1(1-L^m_{r,i,i+1}-B^m_{r,i,i+1}-L^m_{r,i+1,i+2}+B^m_{r,i+1,i+2})(e_{elec}+\varepsilon_{mp}d^4_{i+2,i+3}) \\
&+ Pl_1(1-L^m_{r,i,i+1}-B^m_{r,i,i+1}-L^m_{r,i+1,i+2}+B^m_{r,i+1,i+2})(e_{elec}+\varepsilon_{mp}d^4_{i+2,i+3}) \\
&\quad \sum_{s=1}^{m}(L^s_{r,i+2,i+3}+B^s_{r,i+2,i+3}) + \ldots \\
&= Pl_1\sum_{i=1}^{Kri}(e_{elec}+\varepsilon_{mp}d^4_{i,i+1}) \\
&- Pl_1\sum_{j=1}^{Kri-1}(e_{elec}+\varepsilon_{mp}d^4_{j+1,j+2})\sum_{i=1}^{j}(L^m_{r,i,i+1}+B^m_{r,i,i+1}) \\
&+ Pl_1\sum_{j=1}^{Kri}((e_{elec}+\varepsilon_{mp}d^4_{j,j+1})\sum_{s=1}^{m}(L^s_{r,i,i+1}+B^s_{r,i,i+1})) \\
&- Pl_1\sum_{j=1}^{Kri-1}((e_{elec}+\varepsilon_{mp}d^4_{j+1,j+2})\sum_{i=1}^{j}(L^m_{r,i,i+1}+B^m_{r,i,i+1}) \\
&\quad \sum_{s=1}^{m}(L^s_{r,i+1,i+2}+B^s_{r,i+1,i+2}))
\end{aligned}
$$

The total energy required to transmit all ACK packets generated in the network by the intermediate CHs constituting the route r due to generation of P packets by source CH_i is,

$$\begin{aligned}
E_{rit}(A) &= Pl_3(e_{elec}+\varepsilon_{mp}d^4_{i,i+1})(1-L^m_{r,i,i+1}-B^m_{r,i,i+1}) \\
&+ Pl_3(e_{elec}+\varepsilon_{mp}d^4_{i+1,i+2})(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(1-L^m_{r,i+1,i+2}-B^m_{r,i+1,i+2}) \\
&+ Pl_3(e_{elec}+\varepsilon_{mp}d^4_{i+2,i+3})(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(1-L^m_{r,i+1,i+2}-B^m_{r,i+1,i+2}) \\
&\quad (1-L^m_{r,i+2,i+3}-B^m_{r,i+2,i+3})+\ldots \\
&= Pl_3\sum_{j=1}^{Kri}(e_{elec}+\varepsilon_{mp}d^4_{j,j+1})\prod_{i=1}^{j}(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})
\end{aligned}$$

The total energy required for receiving data packets by intermediate CHs of the route r is,

$$\begin{aligned}
E_{rir}(D) &= (Kri-1)Pl_1e_{elec}-Pl_1e_{elec}\sum_{i=1}^{Kri-2}(L^m_{r,i,i+1}+B^m_{r,i,i+1}) \\
&+ Pl_1e_{elec}\sum_{i=1}^{Kri-1}\sum_{s=1}^{m}(L^s_{r,i,i+1}+B^s_{r,i,i+1}) \\
&- Pl_1e_{elec}\sum_{i=1}^{Kri-2}(L^m_{r,i,i+1}+B^m_{r,i,i+1})\sum_{s=1}^{m}(L^s_{r,i+1,i+2}+B^s_{r,i+1,i+2})
\end{aligned}$$

The total energy consumption by CHs of the route r for receiving ACK packets is,

$$\begin{aligned}
E_{rir}(A) &= Pl_3e_{elec}(1-L^m_{r,i,i+1}-B^m_{r,i,i+1}) \\
&+ Pl_3e_{elec}(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(1-L^m_{r,i+1,i+2}-B^m_{r,i+1,i+2}) \\
&+ Pl_3e_{elec}(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})(1-L^m_{r,i+1,i+2}-B^m_{r,i+1,i+2}) \\
&\quad (1-L^m_{r,i+2,i+3}-B^m_{r,i+2,i+3})+\ldots \\
&= Pl_3e_{elec}\sum_{j=1}^{Kri-1}\prod_{i=1}^{j}(1-L^m_{r,i,i+1}-B^m_{r,i,i+1})
\end{aligned}$$

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