On Network Lifetime Maximization in Wireless Sensor Networks with Sink Mobility

By

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CIIT/SP12-PEE-004/ISB

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A Post Graduate Thesis submitted to The Department of Electrical Engineering as partial fulfillment of the requirements for the award of Degree of PhD in (Electrical Engineering)

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It is certified that Mariam Akbar, CIIT/SP12-PEE-004/ISB has carried out all the work related to this thesis under my supervision at the Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad and the work fulfills the requirement for award of PhD degree.

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DEDICATION

This thesis is dedicated to my parents and parents-in-law for their endless support, love, and encouragement.

I lovingly dedicate this thesis to Kashif (my husband) and to Hussain, Mahad & Zainab (my kids) whose patience supported me throughout this endeavor.

I dedicate this thesis to Dr. Nadeem Javaid (my supervisor) who has made me stronger and more fulfilled than neither I was nor I have ever imagined.

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ABSTRACT

On Network Lifetime Maximization in Wireless Sensor Networks with Sink Mobility

Wireless Sensor Networks (WSNs) extend human capability to monitor and control the physical world, especially, in catastrophic/emergency situations where human engagement is too dangerous. There is a diverse range of WSN applications in terrestrial, underwater and health care domains. In this regard, the wireless sensors have significantly evolved over the last few decades in terms of circuitry miniaturization. However, small sized wireless sensors face the problem of limited battery/power capacity. Thus, energy efficient strategies are needed to prolong the lifetime of these networks. This dissertation, limited in scope to routing only, aims at energy efficient solutions to prolong the lifetime of terrestrial sensor networks (i.e., WSNs) and Underwater WSNs (UWSNs).

In WSNs, we identify that uneven cluster size, random number of selected Cluster Heads (CHs), communication distance, and number of transmissions/receptions are mainly involved in energy consumption which lead to shortened network lifetime. As a solution, we present two proactive routing protocols for circular WSNs; Angular Multi-hop Distance based Clustering Network Transmission (AM-DisCNT) and improved AM-DisCNT (iAM-DisCNT). These two protocols are supported by linear programming models for information flow maximization and packet drop minimization. For reactive applications, we present four routing protocols; Hybrid Energy Efficient Reactive (HEER), Multi-hop Hybrid Energy Efficient Reactive (MHEER), HEER with Sink Mobility (HEER-SM) and MHEER with Sink Mobility (MHEER-SM). The multi hop characteristic of the reactive protocols make them scalable. We also exploit node heterogeneity by presenting four routing protocols (i.e., Balanced Energy Efficient Network Integrated Super

Heterogeneous (BEENISH), Mobile BEENISH (MBEENISH), improved BEENISH (iBEENISH) and improved Mobile BEENISH (iMBEENISH)) to prolong the network lifetime. Since the problems of delay tolerance and mobile sink trajectories need investigation, this dissertation factors in four propositions that explore defined and random mobile sink trajectories. On the other hand, designing an energy efficient routing protocol for UWSNs demands more accuracy and extra computations due to harsh underwater environment. Subject to nodes' energy consumption minimization, we present Autonomous Underwater Vehicle (AUV) and Courier Nodes (CNs) based routing protocol for UWSNs. We validate our propositions for both WSNs and UWSNs via simulations. Results show that the proposed protocols where we incorporated sink mobility perform better than the existing ones in terms of selected performance metrics.

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30 Mariam Akbar, Nadeem Javaid, Zahoor Ali Khan, Umar Qasim, Turki Ali Alghamdi, Saad Noor Mohammad, Syed Hassan Ahmed, Majid Iqbal Khan, and Safdar Hussain Bouk. "Towards network lifetime maximization: sink mobility aware multihop scalable hybrid energy efficient protocols for Terrestrial WSNs." International Journal of Distributed Sensor Networks, 11, no. 10 (2015): 908495. (IF=1.239) Download

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Chapter 1

Introduction

1.1 Wireless Sensor Networks

Wireless Sensor Networks (WSNs) consist of distributed autonomous devices that are able to monitor physical or environmental conditions. These networks enables to remotely monitor the field. WSNs can be used on ground (Terrestrial Wireless Sensor Networks (TWSNs)), on body (Body Area Network (BAN)), in water (Underwater Wireless Sensor Networks (UWSNs)), etc. In this dissertation we consider TWSNs and UWSNs.

1.1.1 TWSNs

A WSNs is shown in figure 1.1, (where, Base Station (BS), Cluster Head (CH) and nodes are shown). Huge number of applications of WSNs cover many areas such as military applications (security monitoring, detecting potential nuclear attacks, targeting, secure communication, and surveillance), health applications (monitoring blood pressure, body temperature, cardiac activity, etc.) and environmental applications (air pollution, flood or fire detection, weather forecasting, traffic control, etc.) [1, 2, 3, 4].

A typical autonomous device that is a sensor node, performs sensing (sensors), analog to digital conversion, processing (processor/controller and memory), and communication (transceiver). All these processes are powered by a battery unit as shown in figure 1.2 ([1]). These units enable the sensors to sense the physical attribute from the environment, collect and process the sensed information and then transmit it to the sink.

Nodes are independent when deployed in the field because these are able to self-configure and survive. However, it is difficult to recharge their batteries. So, energy consumption of these nodes should be as minimum as possible if appreciable

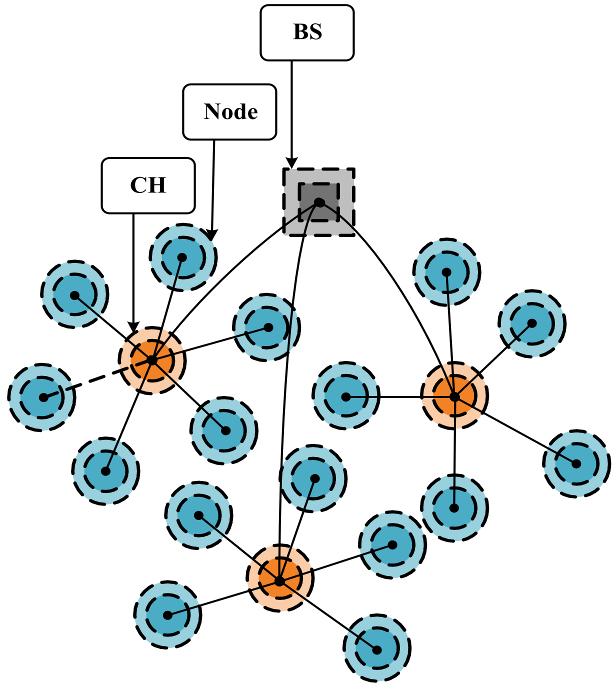


FIGURE 1.1: A typical WSN

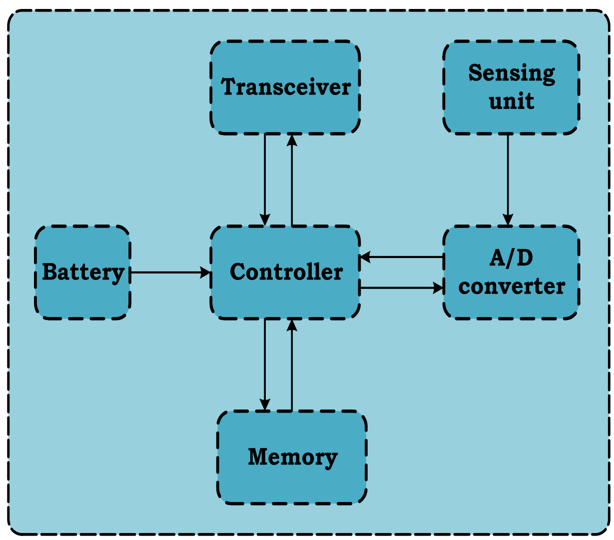


FIGURE 1.2: Node architecture

network lifetime is expected. To achieve fault tolerance, usually WSNs consist of hundreds or even thousands of sensor nodes [5, 6, 2].

Methods of data delivery from nodes to BS depend on application and they can be categorized into four types; continuous, query driven, event driven, and hybrid. The first method allows each node to transmit data periodically. In the second method, data is transmitted when a query is generated by sink. Similarly, event driven transmission is triggered by occurrence(s) of specific event(s). A hybrid data delivery method utilizes two or more methods at the same time. Routing protocols are highly influenced by these data delivery methods in terms of energy consumption [7, 8]. Therefore, selection of proper data delivery method is one of the major challenges faced by the sensor network routing protocols.

As each node is equipped with limited energy source; usually a battery. Therefore, proper route selection for data transmission is of extreme significance [9, 10, 11, 12]. In [2], authors discuss the relation between hop count and energy consumption on theoretical as well as practical point of view. For example, considering the case of single hop communication where each node directly sends data to sink, thereby penalizing distant nodes in terms of energy consumption (refer figure 1.3). On the other hand, multi hop transmission runs out the battery of nearer nodes more quickly as compared to the distant ones as shown in figure 1.3. Therefore, clustering is required to balance the energy consumption of farther as well as nearer nodes. Prior to routing, random deployment of nodes leave some regions un-monitored. So the placement of sink should be such that it can conveniently get packets from every part of network.

Many protocols use clustering as their routing scheme [13]- [19] as this technique is very effective for data transmission in WSNs. In this technique, the member nodes of a cluster select a CH among themselves for a particular round. All the cluster members send data to their respective CH. The CH receives that data, aggregates it and then sends it to the BS. Aggregation gets rid of redundant data and only useful data is sent to base station which saves energy. Clustering can be done in two types of networks, i.e., homogeneous and heterogeneous. In homogeneous WSNs, all nodes have the same initial energy level, whereas, networks with different node energy levels are termed as heterogenous networks. Multi-hoping between CHs is

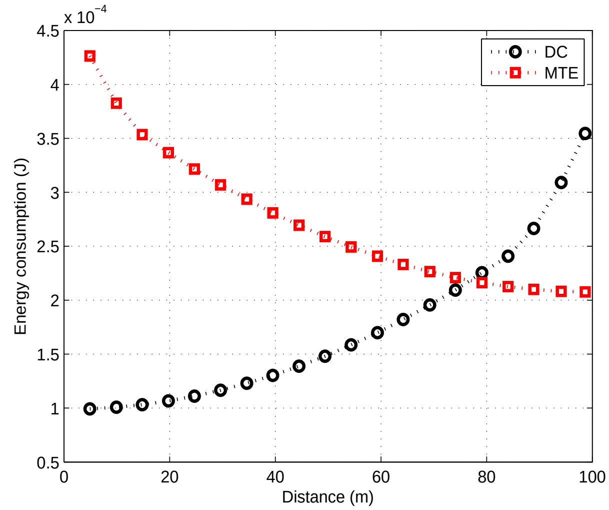


FIGURE 1.3: Energy consumption comparison: Direct Communication (DC) vs Minimum Transmission Energy (MTE)

used to extend the lifetime of large scale networks [20].

Protocols can be classified as proactive [15] and reactive [14]. When the nodes periodically send their data to the BS, these are referred as proactive. These protocols send information of relevant parameters after a fixed period of time. These types of networks are usually used for applications requiring periodic data monitoring. When the nodes react immediately to sudden and drastic changes in the value of the interested parameter then the protocols are said to be reactive. In reactive protocols, node does not have to wait for a fixed period of time to sense and transmit the data. Sensors switch on their transmitters whenever there is a drastic change in the value of interested parameter. These protocols are suited for time critical applications.

Network lifetime of WSN is directly proportional to the energy efficiency of the network. Generally nodes are deployed in the network in an ad hoc manner because of vast geographical areas. Nodes wirelessly connect with each other or sink and form a self-organized network. Thus, WSNs do not need pre-installed wire or existent infrastructure. Due to this feature, it is easy and cheap to install WSN in the area of interest.

Among communication bandwidth, storage and computation capacity, limited power supply is a major constraint. As these nodes are equipped with limited battery power, they become nonfunctional (dead) once the battery is drained. The death of node can cause disconnection of the information. With the death of many nodes, network may split and cause hindrance to the information to reach sink. Energy management plays a vital role in the network lifetime maximization. Nodes consume energy during sensing, reception and relaying, and transmission of data (please see eqns. 1.1, and 1.2).

$$E_{TX} = E_{elec}k + \epsilon_{fs}kd^2 \tag{1.1}$$

$$E_{TX} = E_{elec}k + \epsilon_{amp}kd^4 \tag{1.2}$$

where E_{TX} is the energy consumed in transmission, E_{elec} is the per bit energy required to run the circuitry, k is the total number of bits per packet, ϵ_{fs} is the radio parameter used to achieve an acceptable SNR ratio when d is less than the reference distance, ϵ_{amp} is the radio parameter used to achieve an acceptable SNR ratio when d is greater than or equal to the reference distance, and d is the communication distance.

1.1.2 UWSNs

UWSNs are also getting popular due to their advantages like pollution monitoring, oil extraction monitoring and aquiculture monitoring [21]. However, radio and optical signals are affected by huge amount of scattering and absorption loss in aqueous environment. Thus, acoustic signals are typically used for communication in underwater which undergo high delay in communication because of its speed ($1500m/s$). Unlike Terrestrial WSNs, acoustic channels have high energy consumption, limited bandwidth and low transmission speed, shown in table 1.1 [22]. The underwater nodes can bear harsh weather conditions in deep sea. These nodes are also supplied with limited battery capacity and are expected to stay alive on batteries for longer duration of time without getting recharged [21].

Sink mobility is among the effective means to minimize/balance energy consumption of the nodes while maximizing throughput in both WSNs and UWSNs. Mobile Sink (MS) is an Unmanned Aerial Vehicle (UAV) that has no energy constraint. It can easily move within the network field to receive data from the CHs or even directly from the nodes. In this way, the communication distance is significantly minimized that factors in network lifetime prolongation. The MS follows either defined or random trajectories while moving in the network field. The goal of this dissertation is to contribute in new energy efficient routing solutions that involve MSs in WSNs and UWSNs. For this purpose, comprehensively overview and evaluation of existing routing strategies in terms of network lifetime prolongation and throughput maximization is needed.

The rest of the dissertation is organized as follows. In chapter 2, state of the art literature review is conducted. In chapters 3, 4 and 5, we propose three different routing schemes, where, initially network has clustering and CHs receive and forward data from member nodes. After that we deploy an MS that moves in the network and receives data from CHs. The results of both clustering and sink mobility are compared. The hybrid schemes, where clustering and MS are considered, perform well. In chapter 6, we consider sink mobility only and explore the trajectories of sink. Where, sink moves in the network field and gather information directly from the nodes. We compare the results with existing schemes that have clustering and sink mobility. The results show that our proposal achieves longer network lifetime, stability period and throughput. In chapter 7, we propose a routing protocol for UWSNs. We consider a three dimensional field. For

TABLE 1.1: Characteristic difference between WSN and UWSN

Feature	Terrestrial	Underwater
Signal	Radio	Acoustic
Speed	Light speed (3×10^8m/sec)	Acoustic signal speed 1500 m/sec
Anchor	GPS-based	AUV
Signal bandwidth	High	Low
Location error rate	Low	High
Device mobility	Static and mobile	Static and mobile
Propagation delay	Low	High
Power source	Battery, solar	Battery

data gathering, we deploy an MS (Autonomous Underwater Vehicle (AUV)) and courier nodes. In UWSN, acoustic model is used for communication because of change of medium, shown in table 1.1.

1.2 Research challenges

WSNs are getting more attention day by day due to their potential applications. They are easy to deploy and their main responsibility is to sense the desired attributes of the network field. After sensing the information they transmit (send) it to the BS (sink) for further processing. Mainly node consumes energy in sensing and sending data to the sink. Nodes have limited resources in terms of energy, also the wireless links are low power and unreliable. In this case there is a design challenge for reliable data delivery. Different applications impose different challenges for efficient and reliable data delivery. With the development in the research and applications in WSNs, many challenges are identified [13, 16, 22] e.g.

- Localization,

- Homogenous and heterogeneous networks,
- Group management,
- Static and dynamic clustering,
- Dependability,
- Topology control,
- Static or MS and its optimal number,
- Self-calibration,
- Self-healing,
- Clock synchronization,
- Data aggregation,
- Query processing,
- Parameters to evaluate the network performance,
- Sensor processing and fusion under limited capacities,
- Debugging and testing, etc.

1.2.1 Challenges addressed

This thesis investigates various approaches for improving the network lifetime and validates them through simulations. Moreover, from above mentioned challenges this thesis addresses the following research challenges:

Challenge 1: How does static clustering minimize the energy consumption of nodes and then overall energy consumption of the network?

Challenge 2: How does heterogeneity affect the performance of the network?

Challenge 3: Role of sink mobility in network for lifetime improvement. Do sink trajectories play any role in achieving maximized network lifetime?

Challenge 4: Which mathematical technique could help to achieve maximum network lifetime?

Challenge 5: Which are the best suited parameters to evaluate performance of a network?

Challenge 6: What is optimal number of MSs in a network?

1.2.2 Contribution towards addressed challenges

Publication list included in this thesis:

a. Mariam Akbar, Nadeem Javaid, *et al.*, "Towards Network Lifetime Maximization: Sink Mobility Aware Multihop Scalable Hybrid Energy Efficient Protocols for Terrestrial WSNs," International Journal of Distributed Sensor Networks, vol. 2015, Article ID 908495, 16 pages, 2015. doi:10.1155/2015/908495. (IF=0.665).

Relevance to thesis:

i. This paper supports the work presented in paper b and c,

ii. This paper provides the answer to challenges 1, 3 and 4,

iii. This paper is part of chapter 4 in the thesis.

b. Mariam Akbar, Ashfaq Ahmad, Nadeem Javaid, Muhammad Imran, Athanasios Vasilakos and Areeba Rao, "A multihop angular routing protocol for wireless sensor networks", Journal of Sensors, 2016. (IF=1.182)

Relevance to thesis:

i. This paper supports the work presented in paper a,

ii. This paper provides the answer to challenges 1, 3 and 4,

iii. This paper is part of chapter 3 in the thesis.

c. Mariam Akbar, Nadeem Javaid, Majid Iqbal Khan, Muhammad Imran and Mohsen Guizani, "Sink mobility aware energy efficient network integrated super heterogeneous protocol for WSNs", EURASIP Journal on Wireless Communications and Networking 2016, no. 1 (2016): 1. (IF=0.72)

Relevance to thesis:

i. This paper supports the work presented in papers a and b,

ii. This paper provides the answers to challenges 3 and 5,

iii. This paper is part of chapter 5 in the thesis.

d. M. Akbar, N. Javaid, A. A. Khan, Z. A. Khan, U. Qasim, "On Modeling Geometric Joint Sink Mobility with Delay-tolerant Cluster-less Wireless Sensor Networks", 4th IEEE Technically Co-Sponsored International Conference on Smart Communications in Network Technologies (SaCoNet13) 2013, France.

Relevance to thesis:

i. This paper supports the work presented in papers e,

ii. This paper provides the answers to challenges 3, 5 and 6,

iii. This paper is part of chapter 6 in the thesis.

e. Mariam Akbar and Nadeem Javaid, "Defined and Random Trajectories of MS in Homogeneous WSNs with Balanced Transmission," accepted in Wireless Networks, 2016. (0.961)

Relevance to thesis:

i. This paper supports the work presented in papers d,

ii. This paper provides the answers to challenges 3, 4, 5 and 6,

iii. This paper is part of chapter 6 in the thesis.

f. Mariam Akbar, Nadeem Javaid, Ayesha Hussain Khan, Muhammad Imran, Muhammad Shoaib and Athanasios V. Vasilakos, "Efficient data gathering in 3D linear underwater wireless sensor network using sink mobility," Sensors 16, no. 3 (2016): 404. (IF=2.245)

Relevance to thesis:

i. This paper supports the work presented in papers g in underwater environment (three dimensional with acoustic communication).

ii. This paper provides the answers to challenges 3, 4, 5 and 6.

iii. This paper is part of chapter 7 in the thesis.

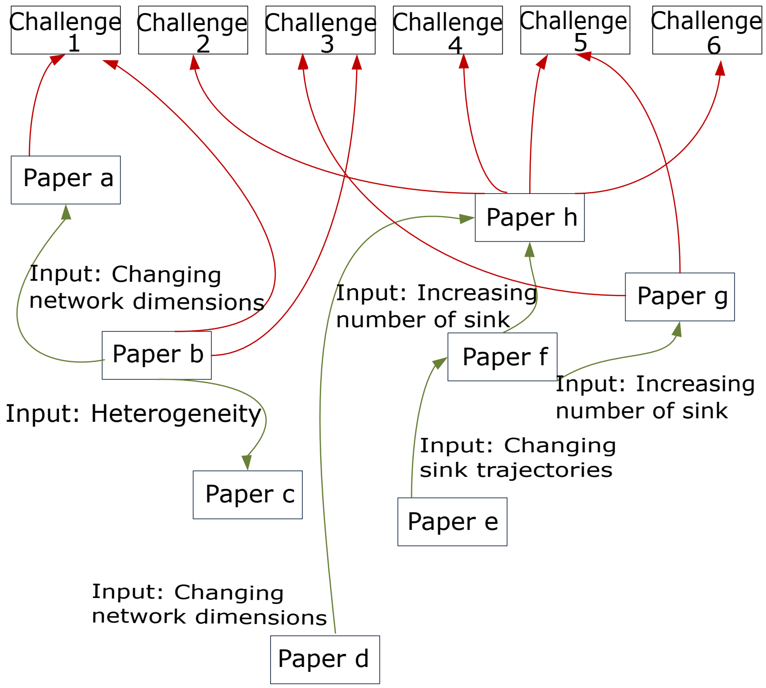


FIGURE 1.4: Relationships between the papers included in the dissertation and their contributions.

1.2.3 Impact of thesis

The impact of this thesis is two-fold. First, the proposed strategies for data gathering and mathematical modeling gives a brief overview of clustering and sink mobility schemes. It shows that sink mobility reduce the energy consumption of nodes and ultimately network lifetime is prolonged. Second, simulation results validate that the proposed models achieve the prolonged network lifetime. We give the brief introduction about WSNs and highlight research challenges. Moreover, contributions link with the challenges is also provided. In next chapter brief overview of existing schemes is provided.

Chapter 2

Related work

2.1 Chapter summary

In this chapter, a brief overview of related research work is presented. We review two environments of WSNs: terrestrial and underwater. In TWSNs we use first order radio model, while in UWSNs acoustic model is applied. In both environments we applied sink mobility and analyzed network lifetime, throughput, packet dropped ratio and delay.

2.2 Routing protocols for TWSNs

In order to achieve energy efficiency at network layer in WSNs, many routing protocols have been proposed. These protocols decide routing path for delivering data to end station [15]. Generally, routing protocols can be divided into two categories: cluster based routing protocols and MS based routing protocols.

2.2.1 Routing protocols with clustering

Initially, we study the cluster organization in hierarchical routing protocols. Then to minimize energy consumption, role of CH is replaced with MS.

For routing in WSNs, LEACH (Low Energy Adaptive Clustering Hierarchy) [13] is a first hierarchical clustering algorithm which randomly selects nodes as CHs. Basically, LEACH works in two phases; set up phase and steady state phase. In set up phase, nodes are randomly deployed in network field such that each node is initially equipped with equal energy. Deployment is followed by random selection of CHs where each node generates a random number and compares it with a threshold value. If the generated random number is less than the threshold value, then that node is selected as CH for the current round. Soon after the selection of CHs, remaining nodes associate themselves with the nearest CH. In steady state phase, TDMA based schedules are assigned to nodes and CHs for data transmission such that each node or CH associates within its allocated time slot only. Thus, we can say that LEACH uses two modes of communication i.e., between nodes and CHs, and between CHs and BS. LEACH-Centralized (LEACH-C) [23] uses centralized clustering algorithm, where, the information about the energy and location of nodes is sent to BS. The CH selection is random in LEACH-C. In multihop-LEACH [24], data sent by nodes is received at BS through a chain of CHs. Advanced-LEACH (A-LEACH) [25] selects CHs on the bases of current state and random probability. Network lifetime is prolonged by increasing the data forwarding burden on certain nodes. A model is proposed in [26] that utilized clustering mechanism by changing the selection criteria of CH and gave better performance.

TEEN (Threshold Sensitive Energy Efficient Sensor Network protocol) [14] is the first reactive protocol for homogeneous WSNs proposed by A. Manjeshwar and D. P. Agarwal in 2001. It is a reactive protocol for time critical applications. In this scheme, CH broadcasts two threshold values i.e. Hard Threshold (HT) and Soft Threshold (ST). HT allows nodes to transmit the event, if the event occurs in the range of interest. Therefore, this not only reduces the number of transmissions but also increases network lifetime. The set up phase of TEEN is similar to that of LEACH, where CHs are randomly selected from the set of eligible nodes. Whereas, data is not transmitted until the threshold is reached in steady state phase. The disadvantage of this scheme is that if the network couldn't get operational until HT arrives. If network does not observe HT, user will not receive ant data from the network and even no information weather any node is alive. That is why TEEN is not a good option for applications that require periodic data monitoring.

TABLE 2.1: Comparative analysis of the hierarchical routing protocols in TWSNs

Protocol	**Node deployment**	**Sensor batteries**	**Control mechanism**	**Route processing**	**Network lifetime**	**Throughput**	**Delay**
LEACH	Random	Homogeneous	Centralized	Proactive	+	++	+
LEACH-C	Random	Homogeneous	Centralized	Proactive	+++	+++	++
multihop-LEACH	Random	Homogeneous	Centralized	Proactive	++	++	++
S-LEACH	Random	Homogeneous	Centralized	Proactive	++	++	+
A-LEACH	Hybrid	Homogeneous	Centralized	Proactive	++	++	+
TEEN	Random	Homogeneous	Centralized	Reactive	+++	+	++++
AP-TEEN	Random	Homogeneous	Centralized	Reactive	+++	+	++++
SEP	Random	Heterogeneous	Centralized	Proactive	++	++	+++
DEEC	Random	Heterogeneous	Distributed	Proactive	+++	+++	++++

APTEEN (Adaptive Threshold sensitive Energy Efficient sensor Network protocol) [27] sends data periodically and also provide information on time-critical events. SEP (Stable Election Protocol) [15] is the first heterogeneity aware WSN protocol which uses proactive data reporting. The authors consider two levels of energy in a hierarchical network such that each node independently elects itself as a CH based on probability value. Intuitively, advanced nodes have more probability to become a CH than normal nodes, which seems logical according to their energy consumption. The drawback of SEP is that it does not consider the changing residual energy of the node hence, the probability of advanced nodes to become CH remains high irrespective of the residual energy left in the node. Moreover, SEP performs below, if the network is more than two levels. Following the same technique as that of LEACH, data scheduling and transmissions occur in SEP as well. In [28], authors propose Enhanced-SEP (E-SEP) routing protocol for heterogeneous WSNs. The proposed proactive E-SEP protocol extends the concept of SEP from two level heterogeneity to three levels.

DEEC [29] (Distributed Energy Efficient Clustering) generalizes the concept of SEP to muti energy levels in a homogeneous proactive environment. This protocol selects CHs on the bases of nodes' residual energy and average energy of the network. Soon after the CHs selection, minimum distance based association of nodes with CHs takes place. Finally, BS assigns TDMA based schedules to nodes as well as CHs. In these schedules, data transmissions from nodes to their respective CHs and from CHs to BS occur. The node with higher initial and residual energy has more chances to become a CH than the low residual energy node. DEEC performs well in multi-level heterogeneous WSN as compared to LEACH and SEP. Stochastic Distributed Energy-Efficient Clustering (SDEEC) [30] introduces a balanced method for CH election. Comparative analysis of hierarchical routing protocols is given in 2.2.1. This method is more efficient than previous techniques as it uses stochastic scheme detection. SDEEC out performs SEP and DEEC in terms of network lifetime.

In EACLE [31], route selection is executed independently after the CH selection. This two-phase control approach increases overheads and reduces the battery power, which shortens the lifetime of WSNs. To cope with this problem, authors propose a clustering based routing protocol 'PARC' for WSNs which reduces these overheads.

HEED [32] is a distributed clustering algorithm which stochastically selects the CHs. This hybrid approach selects CHs on the basis of probability and minimizes the energy cost by association mechanism. This algorithm exploits the availability of multiple transmission power levels of nodes and correlates the selection probability of each node to its residual energy.

DDEEC [33] selects CHs on the basis of residual energy of nodes. Thus, makes the advanced nodes more probable to be selected as CHs during initial rounds as compared to normal nodes. As the initial energy of nodes steps down with the passage of time, advanced nodes will have the same CH selection probability like the normal ones.

P. Saini *et al.* [34] propose EDEEC protocol which extends the concept of heterogeneity to three energy levels by adding super nodes.

2.2.2 Routing protocols with sink mobility

Authors in [35] introduce Hierarchical Ring Location Service (HRLS) protocol; a practical distributed location service which provides sink location information in a scalable and distributed manner. In contrast to existing hierarchical-based location services, each sink in HRLS distributively constructs its own hierarchy of grid rings.

In [36], authors propose a novel method for MS operation in which the probe priority of MS is determined from data priority to increase the QoS. They use MS to reduce routing hot spot.

In [37], authors investigate the joint sink mobility and routing problem. They first solve the problem by primal dual algorithm while considering single BS and then it is generalized with the consideration of multiple BSs. Authors in [38] use mobile BS to maximize the lifetime of WSNs, where, the BS moves with a finite speed to collect data from static nodes. In [39], authors increase the network lifetime by deploying multiple BSs where Mixed Integer Linear Programming (MILP) is used to determine the position as well as traffic flow from/towards the mobile BS.

Efficient Scheduling for the MS in WSNs with Delay Constraint (ESWC) is proposed by Yu Gu *et al.* in [40]. This protocol implements sink mobility to improvement the network lifetime. It also bounds the delay caused by the movement of the sink. A general and practical unified formulation is also provided in this scheme that analyze the jointly the sink mobility, routing and delay of the network. The authors also propose polynomial-time optimal algorithm. They compare the advantages of MS in the network with that without MS. This protocol also discusses different sink trajectories and their effects on the lifetime, delay and throughput. Also in [41], the authors implement the sink mobility technique to improve the network lifetime and the stability region. As the MS is driven by petrol or electricity. This protocol also, bounds the travel distance of MS to avoid data loss during the transition of MS between sink locations. When MS stops at a certain sink stop, routing tree is constructed and it causes overhead. To avoid it sink stops at a stop for a definite amount of time on each stop. The authors in this paper defined that the sojourn trip of a MS is the sum of sojourn times in the trip. The authors first formulated the problem as a MILP with objective of maximizing the sum of sojourn times in the whole trip. Due to its NP-hardness, they then devised a novel heuristic for it. Then they conducted extensive experiments by simulations to evaluate the performance of the proposed algorithm in terms of network lifetime.

The authors in [42] also improved the network lifetime by jointly considering sink mobility as well as routing by considering sink to the finite locations. They also proved the NP-hardness of their proposed model implementing multiple MSs. They proved the NP-hardness of the problem and also investigated the induced subproblems. They developed an efficient primal-dual algorithm to solve the subproblem involving a single sink, then they generalized this algorithm to approximate the original problem involving multiple sinks. Finally, they applied the algorithm to a set of typical topological graphs; the results demonstrate the benefit of involving sink mobility, and they also suggested the desirable moving traces of a sink.

In WSNs, sink mobility balances the nodes energy consumption. Nodes have to reconstruct the routes for data transmission when MS moves towards next stop. During transition time, data dissemination is a challenging task. In [43], authors proposed a Virtual Grid Based Dynamic Routes Adjustment (VGDRA) scheme. It reduces the route reconstruction cost of nodes. For this purpose they optimize the sink location and also define communication rules. Few nodes, reconstruct their routes to re-adjust the path with the sink. Through this scheme they extend the network lifetime.

In [44], authors proposed a Lifetime Optimization Algorithm with MS nodes for WSNs based on location information (LOA MSN). For obtaining the location information of nodes authors used satellite and RSSI positioning algorithms. They established the movement paths with the help of lifetime optimization and path selection models. Sink obtains the location information of the nodes. Then, through graph theory model, they obtain the movement paths. The MS gathers data from the nodes in the grid center. Through experiments, they show that sink finds optimal path and minimizes nodes' energy consumption cost, which leads to prolonged network lifetime. LOA MSN uses multiple MSs, and minimizes the energy consumption cost, however, it increases data gathering latency.

In [45], authors presented an energy efficient routing scheme that maximizes the network throughput. For data forwarding they use multi-layer clustering design that finds forwarder node. The role of CH rotated among the nodes based on the threshold values, this reduces the number of packet dropped. They use Cluster Designing Algorithm (CDA) architecture for the selection of forwarder node and inter and intra cluster routing, CH rotation and the data delivery all these processes are energy-aware. The experiments show that careful selection of forwarder node leads towards energy efficient routing in intra cluster and inter clusters. It also increases throughput and network lifetime. It is also concluded that CH rotation in each round consumes energy, rather CH works until it consumes a certain amount of energy. After that other suitable node take the charge of CH. Authors, in [46] propose a scheme to improve throughput of the network by considering base station placement problem for WSNs with Successive Interference Cancelation (SIC). Through mathematical model they address this issue. This model is useful to identify a necessary condition for SIC by considering distances from sensor nodes to the base station. To achieve this they divide the network field into feasible regions and select a point in each small region for the stop of base station. The small region with the greater throughput is considered as a solution.

In [47], authors propose a new independent structure based routing protocol which implements sink mobility and provides scalability by exploiting k-level independent grid structure for data dissemination from source to destination. However, independent of the number of movement of both sinks and events, the propsed protocol does not construct any additional routing structure.

Y. S. Yun *et al.* [48] propose a framework to maximize the lifetime of WSNs by using a MS. Authors also formulate linear programming models for static as well as MS. Within a predefined delay tolerance level, each node does not need to send the data immediately as it becomes available. Instead, node can store data temporarily and transmit it when MS arrives at most favorable location for achieving extended network lifetime. Authors in [49] focus on the upper bound of total distance traveled by MS. Authors believe that the inter-transition distance between two successive positions of a MS must be restricted to avoid data loss. Also, considering the overhead on a routing tree construction at each sojourn location of MS, it is required that the MS sojourns for at least a certain duration at each of its sojourn locations.

In [37], J. Luo *et al.* jointly consider sink mobility and routing to maximize data collection during network lifetime.

A distributed localization technique has been presented in [50] for WSNs. In this technique, position estimation is performed by each node in an iterative manner by solving spatially constrained local programs. On the bases of range and estimated position(s), the defined constraints enable the nodes to update their positions on regular intervals. In order to reduce energy consumption of the network, a stopping criteria for wireless transmissions has been introduced.

Routing scheme, based on clustering mechanism; RE-LEACH [51] works on the same principle as LEACH, however, it considers node's residual energy during CH selection. Another scheme, Distributed Regional Energy Efficient Multi-hop Routing Protocol based on Maximum Energy in WSNs (DREEM-ME) [52]; a static clustering based routing protocol, minimizes the distance between nodes and CHs that ultimately saves transmission energy. In this scheme, square area is divided into concentric circles and each ring is further subdivided in to four regions, whereas, central circle remains the same. Eight outer regions are considered as clusters (four clusters are present in each central and outer circle). Each cluster selects CH on the basis of residual energy to gather data from member nodes. CHs in the outermost ring forward their data through relay from central ring's CHs, on the basis of minimum distance. However, energy is still consumed in periodic selection of CH.

DYNamic sink mobility with Need-based Clustering (DYN-NbC) [53] uses both clustering and MS. In this protocol, sink moves to the highest node density region. Whereas, in the other regions of the network field, clusters are formed and the CH selection is based on LEACH criteria. Sink mobility along with clustering, balances energy consumption to some extent, however, clustering itself is an energy consuming process. A MS based Uneven Clustering algorithm (UC-MS), is proposed in [54]. In this scheme, CH receives data from member nodes and waits for MS to stay at closer sojourn location for data transmission. Here, energy consumption of CH is minimized as it sends data at minimum distance, however, energy is still consumed in cluster formation and in the selection of CH.

Routing schemes are used to expedite communication between sink and nodes. In [55], authors proposed an energy efficient use of multiple, MSs which results in longer network lifetime. They used MILP to determine the locations of sink. They concluded that; use of rigorous approach to optimize energy utilization leads to significant increase in network lifetime. Authors used this approach for dense field.

Authors in [56], consider the problem of speed and planning path of data mule (i.e. MS) in WSN. They consider different situations where this problem encounters, like modeling the motion of a data-collecting UAV for structural health monitoring through nodes. They used MS to avoid multi-hop forwarding. These MSs can save energy of node, latency increases. In this paper, authors schedule MS framework to minimize data delivery latency. They formulated the problem and proposed an algorithm to minimize the trade-off between energy consumption and data latency. In some networks, received data is sent to the sink in timely pattern. These networks are designed in such a way that nodes buffer data for some interval. Without being overflow, data is send to the sink through multi-hop forwarding or direct transmission depending upon the distance between the node and sink. These are termed as delay-tolerant networks. Authors in [57], exploited the sink mobility in delay-tolerant WSN by considering optimization problem for discovering trajectories and energy-efficient routing protocol.

Balance-aware Energy-efficient Geographical Routing protocol (BEGR) is proposed in [58]. It considers location and residual energy of node as a cost function to select a relay. This scheme selects next hop node on the basis of maximum residual energy to balance energy consumption among nodes. It also implies, trade-offs between energy-efficiency and energy-balance. The simulation results show that BEGR has longer network lifetime, however, shorter stability period.

In [59], authors proposed a novel joint optimization framework to study the trade-offs between delay tolerant and network lifetime in an MS aided WSN. They also devised a heuristic to find a hop-constrained trajectory for the MS. They also proposed an energy-efficient routing protocol, where, MS for the purpose of data gathering traverses along the fixed trajectory. The experimental results show that the proposed algorithm performs better in terms of network lifetime maximization.

In [60], authors explore the problem of sojourn stop duration on a pre-determined stop for data gathering. They proposed MILP and column generation approaches to address this problem. Column generation approach has special structures of the linear programming formulations for finding shortest paths with non-negative costs.

S. Basagni *et al.* in [61], defined a model, in which sink moves on predefined path.

They exploit MS movement close to different nodes to minimize the energy consumption of the nodes. As a consequence, network lifetime increases. Authors, proposed three schemes that represent different solutions for sink mobility. One of the schemes, computes optimal sink routes and calculates sojourn times through proposed MILP formulation. Also, they considered realistic parameters of WSN and sink mobility. This scheme prolongs the network lifetime by considering MS movements depends upon node's transmission costs in a centralized way. In [62], authors proposed mobility pattern of a MS that takes a discrete form where MS stop time is greater than movement time between two sojourn locations. This approach is investigated for balanced traffic load with MS and it results in improved network lifetime. They also studied the benefits of using MS vs a static sink. Authors simulated both grid network and a special in-building network with nodes forming a ring.

By Using QVF algorithm for target tracking, authors in [63], consider the problem of secure clustering in WSNs. They use Bayesian methods for joint selection of the optimal sensor and detection of malicious node to avoid attacks. Also, they consider the tradeoff between quality of sensed data, transmit power and initial energy of nodes. For detecting malicious nodes, they used the Kullback-Leibler Distance (KLD) between the current target position distribution and the forecasted sensor observation.

In [64], Shi *et al.* proposed a routing Protocol to exploit the broadcast feature of wireless transmission. Control overhead is reduced because it requires no extra control messages for route learning. Overhearing of such data packet provides the route information to the MS and nodes.

MS, in the field, helps in reducing energy utilization of nodes by using direct transmission, whereas, MS needs time scheduling to reduce data losses. Authors in [65], presented a model in which two MSs in a square network are present with different defined trajectories. By introducing two sinks, load is balanced and MSs expedite data gathering process and as a result network lifetime is prolonged. A comprehensive overview of existing WSNs routing protocols with sink mobility is given in 2.2.

TABLE 2.2: Over view of existing WSNs routing protocols with sink mobility

Scheme / Features	**Performance achieved**	**Flaws**	**Comments**
Energy-Efficient Communication Protocol for Wireless Microsensor Networks [26]	Prolonged network lifetime and increased throughput. It is clustering based scheme that reduces global communication.	Clustering process consumes energy moreover during CH selection energy consumption also increases. Selection of CH here depends upon the probability.	This scheme uses adaptive clustering and also number of nodes in each cluster are not fixed. So, node density varies in each cluster. The cluster where node density is high load on CH increases for relaying data and it drains its energy quickly.
Optimizing Energy-Latency Trade-off in WSNs with Controlled Mobility. [28]	MS and data mules are used for multi-hop transmission Latency decreases because this scheme uses optimal path for relaying data with the help of data mules.	Energy consumption increases for finding optimal route. Nodes that relay the data of nodes which are not in the transmission range of MS drain the energies quickly.	This scheme decreases data delivery latency on the cost of node energy which it uses for communication between them for finding optimal routes.
SRP-MS: a new routing protocol for delay tolerant WSNs [32]	Prolonged network lifetime. MS directly communicate and receives data from nodes	MS directly receives sensed data from nodes. Nodes waits for MS to come in their sensing range that increases delay.	Direct communication between MS and nodes reduces global communication between nodes, however it increases end to end in the network.
BEGR [58], multi-hoping with cost function (residual energy of node)	It is loop free and adaptive to dynamic scenarios hence prolongs network lifetime. It also balances energy consumption.	It consumes more energy while selecting forwarder node to balance energy consumption, this process consume extra energy hence this scheme is not energy efficient.	This schemes balances the energy consumption by assigning a cost criteria to the node which includes its residual energy and location. While this scheme is not energy efficient that means nodes consume more energy in finding paths and applying cost for further transmission.
A Study on Cluster Lifetime in Multi-Hop WSNs with Cooperative MISO Scheme [34]	Prolonged network lifetime and minimizes fading through cooperation.	Energy consumes during clustering, also CH relay other CHs data and drain its energy quickly thus its lifetime is short.	For network lifetime maximization linear aggregation is introduced. Where after aggregation amount of data varies directly with the size of cluster.
Network lifetime maximization in delay tolerant WSN [35]	MS and multi-hop, jointly optimize the network lifetime with data delivery delay.	End to end delay increases while applying the heuristics for finding the hop constrained trajectory to MS.	MS increases delay in the network due to multi-hoping. Relay nodes consume extra energy in forwarding the data of far away nodes.
Greedy Maximum Residual Energy (GMRE), OPT and Random Movement (RM) MS [37]	Prolonged network lifetime in OPT, where sink locations are optimally defined in comparison with GMRE and RM.	Latency increases in the GMRE and OPT as compared to RM.	Overall due to mobility network lifetime is increased. Latency increases as nodes send data directly to MS.
MobiRoute: Routing towards a MS for Improving Lifetime in WSN [38]	Prolonged network lifetime, packet delivery ratio increases.	Energy consumption is greater as compared to static sink network.	This scheme considers very small scale network for larger networks where node density is high it may not be such efficient.
DDRP, MS and multi-hoping [75]	DDRP reduces the protocol overhead in comparison, prolonged network lifetime.	Energy consumed during relaying the data of other nodes, also in maintaining the routing table.	MS with multi-hoping increase data latency. Also, nodes consume more energy while relaying data of other nodes.

2.3 Routing protocols for UWSNs

The types of routing schemes used in UWSNs are depth based routing, probabilistic routing and data gathering schemes using AUVs etc. Many techniques introduced CNs in depth based routing to minimize the load on forwarding nodes. Authors, in [66] proposed a depth based routing schemes, they empowered them through delay efficient priority factor and holding time (also delay sensitive). This scheme targets to minimize end to end delay at the cost of decreased throughput of the network. They addressed delay sensitivity through choosing optimal data forwarders in low depth region. Also, to avoid the energy holes and data loss they selected those nodes as forwarders which had high number of neighboring nodes. They also introduced adaptive mobility of CNs. This scheme is localization free.
Wahid and Dongkyun [67] investigate UWSN localization free routing schemes that minimizes energy consumption. During the data forwarding process it considers the residual energy of the node as a routing metric. Authors proposed a directional flooding-based routing protocol [68]. This scheme checks the link quality of nodes that are participating in the flooding. The number of nodes participating in flooding are controlled to avoid packet flooding in the whole field. If there are flooding nodes with poor link quality then Directional Flooding Based Routing (DFR) allows more nodes to forward data. This is done for achieving reliable data delivery. On the other hand, few nodes are enough to forward the data.
Authors proposed a scheme AUV-aided underwater routing protocol (AURP) in [69], it uses controlled mobility of multiple AUVs as well as heterogeneous acoustic communication channels. Role of relay nodes is replaced with AUVs, they collect data from gateway nodes and send it to the sink. In this way the data transmissions are minimized. AURP used controlled mobility of AUV which results in short-range high data rates. By simulation, AURP shows the improved delivery ratio

and minimized the energy consumption of nodes.

Mobicast [70] addressed the energy problem in underwater environment for achieving maximum throughput. Mobicast considered the network which is divided into 3D zones. AUVs moves in the zones for data gathering on predefined path. There are two phases of the protocol: data collection within 3D zone, the second phase is awaking nodes in next zone where AUV is heading for data collection. When AUV enters in the next 3D zone the sensors get into active mode and deliver the sensed data. Due to division of field into different zones and introducing sleep awake modes, this protocol minimizes energy consumption of the nodes. This leads towards maximized throughput of the system.

Underwater deployed nodes have movement due to water currents that leads to affect energy efficiency of network. In underwater, due to long propagation delay, multi-hop transmission is preferred. The nodes closer to the sink get more burden by relaying the data of distant nodes and dissipate energy early, however they minimize the overall energy consumption. In Adaptive Power Controlled Routing protocol (APCR) [71], authors jointly addressed mobility of both surface sink and nodes. Also, coverage through power control capabilities. Authors presented a scheme of an adaptive sink redeployment that reduces total energy consumption in APCR. This strategy does not compromise average end to end delay and delivery ratio. In [72], authors analyzed a heterogeneous underwater network. Nodes have been assigned different categorize based on their functionalities. Head node is selected and it is responsible for gathering data from a neighboring nodes. Head nodes are distributed over the network and they collects the data from respective neighboring nodes and forward the data to an AUV that is taking a data-gathering tour. Selection criteria of head node and its placement is not discussed that leads towards non-uniform energy consumption. The rapid depletion of energy leads towards decreases network lifetime.

In [73], authors used an AUV working as a MS. It effectively saves energy by reducing the transmission range of nodes. The tour points are predefined for data gathering from the network. Due to drastic environmental conditions, nodes are mobile and randomly changing their positions therefore authors called them probabilistic neighborhood of AUV stop. The designed UWSN is three dimensional, where the node depth is same by anchoring them to the ocean floor. AUV is also moving on a constant depth i.e $D_{avu} < D$. In this way authors simplified the problem and they simulated the two dimensional field, with random uniform node distribution at fixed depth D. This two dimensional plane A is divided into several sub-regions which are named as clusters. Initially, when network operation starts, AUV partition the network into cluster through Voronoi generator point and broadcast the cluster information. Nodes use this information to identify the cluster to which they belong. After cluster and nodes association phase MNs selects a delegate node known as CH. The selected CH in each cluster further divides the cluster into several sub-clusters. In each sub-cluster a Path Node (PN) is selected through CH, which gathers primary data from MNs and relay it to the AUV. CH broadcast the PN information throughout the cluster. After this phase, AUV takes another tour which is called data gathering tour it visits each PN of which addresses are informed by the CH. AUV finds theses probabilistic neighborhood of its tour stops for specific time period and it is called probe interval. In the next step AUV identifies the nodes and creates communication schedule for these nodes. AUV waits on each stop until all data is collected from the neighbors. As neighbors are changing due to probabilistic nature, nodes consume non-uniform energy and some nodes deplete more quickly, also end to end delay of the scheme increases.

TABLE 2.3: Over view of existing routing protocols for UWSNs

Scheme	Features	Performance achieved	Cost paid
AURP [69]	Heterogeneous acoustic channel where multiple AUVs gathering data from nodes through gateway nodes.	Maximized delivery ratio, Minimized energy consumption.	Increased delay.
Data collection [73]	AUV collects data from nodes. Network logically divided into four sub regions and each region selects a CH. Each sub-region further divides into clusters and each cluster selects a PN which collects data from MNs and forward it to AUV.	Minimized total energy consumption, maximized throughput and minimized overhead.	End to end delay increases.
Delay-sensitive routing schemes for underwater acoustic sensor networks [66]	Depth based localization free routing. CNs gathers data and forwards it to surface sink.	Minimized total energy consumption, minimized average end to end delay and minimized transmission loss.	Decreased throughput.
EEDBR [67]	Depth based localization free routing. Energy consumption is balanced. Sender based approach, where sender selects a limited number of suitable forwarding nodes.	Extended network lifetime, minimized energy consumption and minimized end to end delay.	Decreased delivery ratio.
DFR [68]	Nodes are location and neighbor aware. Replaces forwarder in case of weak link. Forwarding activity is performed hop by hop. Deliver packets through flooding.	Increased packet delivery ratio and less communication over head.	Increased delay.
Mobicast [70]	Nodes position can be change due to water currents. AUV moves on user defined trajectory and collects data from 3D zones. Nodes record its location in specific time period to calculate the drift and also observe sleep awake mechanism. Capable of covering the drift distance of node.	Minimized delay, increased throughput and increased successful delivery rate.	Increased message overhead and increased power consumption.
Adaptive surfaces sink replacement strategy [71]	Surface sink is capable of self-configuration and has no energy constraint. Sink updates the table of node IDs and their energies, and next time when receive data it compares with the existing record either its same node or changed. If the nodes power level is changed then sink will change its position in (x, y) plane to reduce the distance between nodes to minimize the energy consumption.	Minimizes energy consumption and end to end delay.	Decreased throughput.
Remote data retrieval strategy [72]	Head nodes receives data from the neighbor nodes and forward it to AUV in grid topology.	Increased packet delivery ratio, decreased end to end delay and minimized energy consumption.	Increased end to end delay.

Data gathering is completed in three steps: MN send their sensed data to the PN, in next step PN send the received data to AUV and in final step AUV send all the received data from the PNs to the sink. PNs gather data continuously except the interval in which they transfer their data to the AUV. In the start of data gathering tour AUV visits each cluster and get the list of PNs in that cluster, after obtaining the lists from each cluster, AUV visits each PN in order of the list. After completing one tour AUV returns to start point and send data to the surface sink. TDMA is used for multiplexing the link between MNs and PN. PN assigns the time slots to MNs for data sending. To avoid the interference between the clusters CDMA is employed. CHs with AUV and PN with CH only exchange the control information and they share the contention-based control channel of $F_{control}$. Between AUV and sink, CDMA with dedicated orthogonal code is employed.

Domingo *et. al.* in [74] presented a clustering based scheme. Where network is partitioned into number of clusters and each cluster selects a CH for data gathering from the MNs. There is no MS for data collection from the CHs. CH forward the received data to sink direct or through multi-hoping. In addition, the framework should also be able to handle the selection of each relay-node for a neighborhood in such a way that uniform energy consumption may take place over the network.

Data Driven Routing Protocol (DDRP) [75] has static nodes and MS can move in the network. Deployed nodes and MS have same communication range. Two nodes can communicate if they are within the communication range. MS has unlimited energy while nodes are equipped with limited energy. MS broadcasts a control packet and nodes that receive that packet set themselves as one hop neighbors. This control packet contains the MS identification, time stamp (when control packet is issued) and control interval that can be affected by speed of MS or communication range. The nodes that receive this control packet do not further broadcast it. The data packets contain information about the distance from the MS and it records the shortest distance for data sending. If the value of $Dist2mSink = 2$, it means that node is two hop away from the MS. The maximum allowed value of $Dist2mSink = K$, where, $K \geq 1$. If the value of Dist2mSink is greater than $K + 1$ or greater it means that node has no route to MS. Further the deployed nodes are divided into three types on the basis of their distance from the sink:

i) The nodes that are present in the communication range of MS send their data direct and they are one-hop neighbors (O-nodes).

ii) The nodes sharing the communication range and have valid path to MS are called M- nodes.

iii) The nodes which do not have valid route to the MS and they have infinity hopes are called I-nodes. This protocol has following working principle. Initially at the start of network each node is I-node. Because at that time MS has not started gathering data and none of the node has received any control packet. As far as network evolves MS starts it tour, nodes receive control packet and set themselves as O-nodes in its path. When a potential two hop neighbor over hears a data transmission made by O-node, it updates its routing table. When this two hop neighbor send its data packet it sets its Dist2mSink as two and also include it in data packet send. In this way M- nodes set their routing table for data delivery. A comprehensive overview of UWSN routing protocols is given in table 2.3. Literature review of routing protocols with clustering and sink mobility are presented in this chapter. In the next chapter, clustering schemes is presented and the afterwards role of CHs are replaced with moving BS. We compare the simulation results of both schemes with the existing schemes.

Chapter 3

A multihop angular routing protocol for WSNs

3.1 Chapter summary

In this chapter, we propose two new routing protocols for WSNs. First one is Angular Multi-hop Distance based Clustering Network Transmission (AM-DisCNT) protocol which uses circular deployment of sensors (nodes) for uniform energy consumption in the network. The protocol operates in such a way that nodes with maximum residual energy are selected as CHs for each round. Second one is improved AM-DisCNT (iAM-DisCNT) protocol which exploits both mobile and static BSs for throughput maximization. Besides the proposition of routing protocols, iAM-DisCNT is provided with three mathematical models; two linear programming based models for information flow maximization and packet drop rate minimization, and one model for calculating energy consumption of nodes. Graphical analysis for linear programming based mathematical formulation is also part of this work.

3.2 Motivation

In LEACH, CHs are selected on the basis of probability. While during the phase of selection residual energy of the node is not taken into account. CHs are responsible for the communication between nodes and BS. Also formation of clusters is random that means there is no check that exists on the number of nodes present in the clusters. It may leads towards the loss of data. In LEACH-C, authors consider the residual energy of a node should be greater than the network's average energy for becoming CH that leads to network partition (improper coverage of the network). Moreover, selection of CHs is random like LEACH, thereby, causing nodes to deplete their energies in an unbalanced manner which ultimately leads to decrease network lifetime and throughput. Multihop-LEACH [24] has an extra feature from LEACH and LEACH-C [23] that is the disconnected nodes which are away and not come in the range of any CH, choose a nearby node CH by sending it to request. Rest this scheme follows the same operational criteria as LEACH and LEACH-C, thus possess same problems. TEEN and APTEEN are clustering based schemes. However, due to reactive nature of protocols thresholds are used which make it complex. DEEC has different levels of energy among the nodes and for the selection of CH it considers the residual energy of a node. Number of cluster in the network and number of nodes in the cluster are not fixed that leads towards more energy consumption. We consider the static clustering in our proposed scheme that reduces overall energy consumption of the network. Also, nodes in a cluster send their data on minimum distance to the CH. Our proposed scheme is given below in detail.

3.3 The proposed protocol: AM-DisCNT

In order to cope with the problems stated in motivation section, we propose a new proactive routing protocol; AM-DisCNT, for heterogeneous WSNs. To minimize the energy consumption of nodes, we implemented static clustering in the proposed scheme. This scheme possess direct communication. Detailed description is provided in the following subsections.

3.3.1 Field distribution

AM-DisCNT divides the network area into two concentric circles; inner circle with radius 'r_i' and outer circle with radius 'r_0'. BS is placed at the center of circle. Circular region is considered to get maximum output from every region of the network. Unlike rectangular networks, corner nodes do not consume extra energy during communication. Inner circle nodes directly send the sensed data to BS, whereas, outer circle nodes communicate with their respective CHs.

3.3.2 Architecture

In this section, the schematic diagram of AM-DisCNT is summarized. N nodes are deployed randomly in two circular regions, inner circle and outer circle. The nodes are assumed to be static, i.e, their position does not change after deployment. BS is placed at the center of inner circle and it is fixed. Inner circle nodes directly send sensed information to BS (shown in figure 3.2), whereas outer circle nodes are further organized in eight sub regions as shown in figure 3.1. Each sub region is considered as cluster and they stay same in the whole network lifetime. In outer circle there are eight clusters. In each cluster fix number of nodes are randomly deployed. Nodes in the cluster send the sensed data to the respective CHs as shown in as shown in figure 3.3. After gathering data from member nodes CHs forward it to the BS. CH either send their data directly to the BS or via intermediate nodes depending upon the distance as shown in the figure 3.4. This topology provides complete coverage of the network.

3.3.3 Formation of regions

Outer circle of AM-DisCNT is divided into eight equal regions. Thus, the network area consists of nine regions; inner circular region 'T_1' and eight outer regions (from r_1 to r_8). Area divisioning decreases the communication distance between sender and receiver. T_1 of the network is formed to separate nearer nodes from farther nodes. n_{T1} nodes out of N are randomly deployed in T_1. x and y coordinates of n_{T1} are calculated as:

$$X_{n_{T1}} = r_i \cos(\theta) \tag{3.1}$$

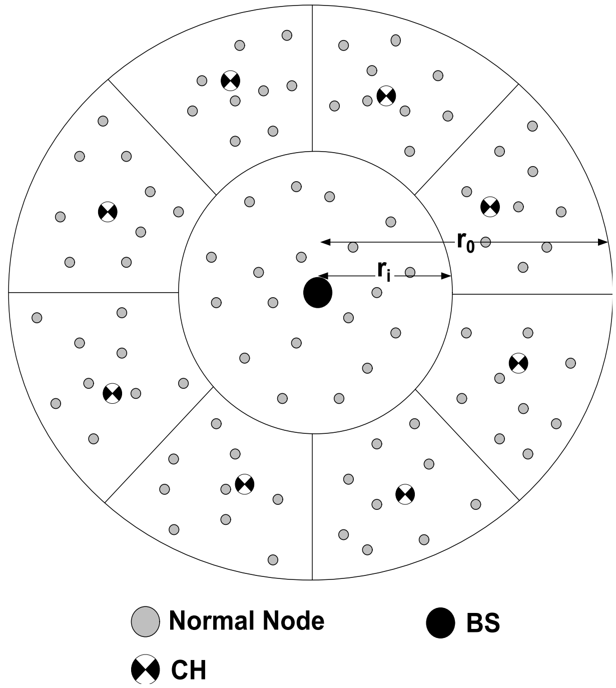


FIGURE 3.1: AM-DisCNT: schematic

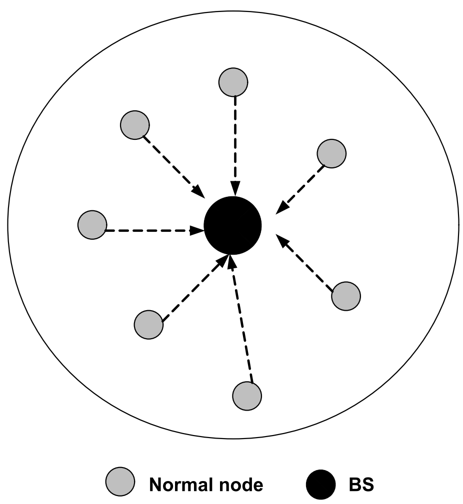


FIGURE 3.2: Inner circle: nodes to BS communication

$$Y_{n_{T1}} = r_i \sin(\theta) \tag{3.2}$$

where, $0 \leq \theta \leq 2\pi$ and $0 < r_i \leq S$. S can be any positive integer. In order to deploy the nodes, we assume the ability to detect the empty areas and the deploy nodes in those empty areas. First of all, n_{T1} nodes are deployed in T_1 then

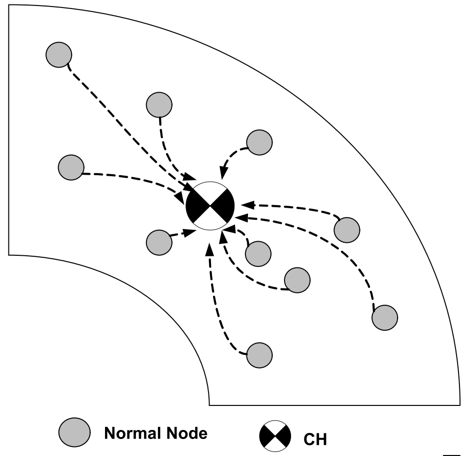


FIGURE 3.3: Outer region: communication of nodes with CH

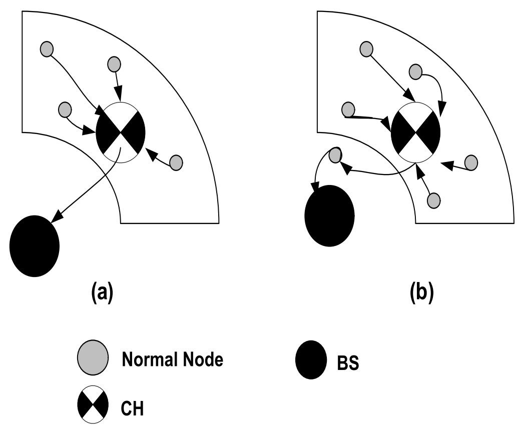


FIGURE 3.4: Communication of CH with BS: (a) directly, (b) through inner circle nodes

the nodes $n_{r1}, ..., n_{r8}$ are deployed in $r_1, ..., r_8$, respectively. We assume that the communication ranges of two adjacent clusters do not overlap. The nodes can communicate with in the clusters, however CHs can communicate to BS or nodes with in the inner circle. The outer eight regions are r_1 to r_8 and the x and y coordinates of nodes in these regions are presented as follows:

$$X_i = r_0 \cos(\theta) \tag{3.3}$$

$$Y_i = r_0 \sin(\theta) \tag{3.4}$$

Here, we consider $n = 0, ..., 8$ and by substituting this value in $n(\pi/4)$ we obtain the variant of θ for $i = 1, ..., 8$. Moreover, $r_0 = r_j = r_{(i+1)} - r_{(i)}$. Through values of θ outer region is partitioned.

3.3.4 Selection of CHs

In each round, eight CHs are selected for outer circular region; one from each subregion. These CHs are selected on the basis of nodes' residual energies. CHs collect data from their own regions and after aggregation send these data to BS. CHs either transmit directly to BS or through inner circle nodes; depending on the residual energy. After the first round, energy of each node is calculated and highest energy nodes are selected as CHs. Such type of clustering ensures maximal area coverage.

3.3.5 Radio model

AM-DisCNT considers first order radio model for energy consumption of nodes; shown in figure 3.5 [29]. In the radio model considered initial energy is $50nJ/bit$ and $\epsilon_{amp} = 100pJ/bit/m^2$. ϵ_{amp} is the radio parameter. It adjusts the desired SNR. During the transmission we also consider the path loss. For the transmission of k bit packet over a distance d we use the equations of radio model, if $d < d_0$ is given in 1.1 and for $d \geq d_0$ is given in 1.2.

The energy consume during the reception of k bit packet is given in following equations,

$$E_{RX} = E_{elec}k \tag{3.5}$$

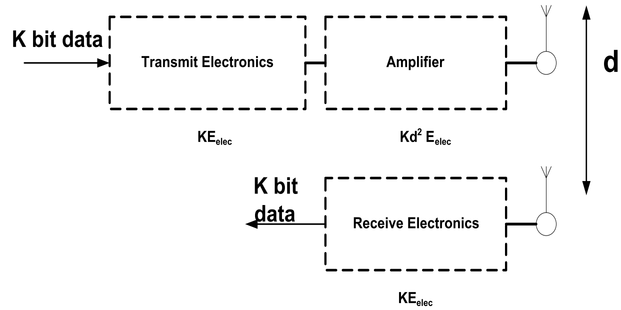


FIGURE 3.5: Radio model

3.3.6 Heterogeneity of the network

We consider a multi level heterogeneous network in such a way that first we develop a two level heterogeneous network model, followed by three level, and finally its generalization into a multi level heterogeneous network model. The nodes with initial energy are considered as normal nodes and their energy is denoted by E_0. Advanced nodes have energy $E_0(1+\alpha)$. N is the total nodes in the network, where m is the fraction of advanced nodes and Nm are the total number of advanced nodes and $(1-m)N$ are remaining nodes that are normal. We calculate the initial energy of the network as:

$$E_{total} = E_0(1-m)N + mNE_0(1+\alpha) \tag{3.6}$$

$$E_{total} = NE_0(1+m\alpha) \tag{3.7}$$

Similarly, for three level heterogeneous networks total energy is given by;

$$E_{total} = NE_0(1+m(\alpha+m_0\beta)) \tag{3.8}$$

in above equation m_0 represents fraction of super nodes and β represents fraction of energy of super nodes in the network.

We design AM-DisCNT multi-level heterogeneous wireless network. In this scheme heterogeneity in terms of energy is introduced which leads towards random energy distribution among all the nodes of the network. The energy of nodes is given by the equation;

$$E_{node} = E_0(1 + t\alpha) \tag{3.9}$$

In the above equation the node is advanced node because it has α times greater energy than initial energy of node. In this way, the total energy of a network is calculated by the following equation. Thus, the total energy of is given by;

$$E_{total} = \sum_{t=1}^{N} E_0(1 + t\alpha) \tag{3.10}$$

3.4 Extending AM-DisCNT: iAM-DisCNT

This section contains five subsections: (i) problem statement, (ii) iAM-DisCNT, (iii) energy consumption calculation, (iv) information flow maximization model, and (v) packet drop minimization model. Details are given in the upcoming subsections.

3.4.1 The problem statement

Proposed AM-DisCNT is design in such a way that reduces the communication distance between nodes and CH in a cluster, as well as between CHs and BS. This scheme has static clustering and once clusters form they remain same. Each cluster has one CH. In this way, energy consumption reduces in each round. AM-DisCNT out performs LEACH, however, in comparison to DEEC, its throughput is less. On average, DEEC outperforms AM-DisCNT; two times out of five. The reason is because in DEEC role of CHs change in each round. If number of CHs are greater, throughput of the network increases.

3.4.2 iAM-DisCNT

iAM-DisCNT has same features as AM-DisCNT except the deployment and operations of BS. Thus, we only discuss placement and working of BS. Three BSs; one static and two mobile, are deployed to maximize the throughput while providing full area coverage.

- **Static BS:** Static BS is deployed in the inner circle of the network area. So, nodes lying in r_i communicate directly with the static BS. Such type of BS deployment minimizes the energy consumption of nodes.
- **Mobile BSs:** Mobile BSs provide energy efficient data collection in WSNs. They collect data (during sojourn intervals), by staying at sojourn locations, directly from nodes as shown in figure 3.6. Where, sojourn location is the location at which any of the two mobile stations stops for data receptions. The time duration for which mobile BS stays at any sojourn location within any of the sub regions is called sojourn time. This technique reduces communication distance between BS and nodes thereby minimizing energy consumption.

iAM-DisCNT considers two mobile BSs moving in outer circle of the network area. The mobile BSs move in a circular trajectory; one in clockwise direction whereas the other in anti clockwise direction, meanwhile collecting data from the nodes. Circular trajectory is a path that is exactly at the middle of outer circle as shown in figure 3.6, circular trajectory of mobile BSs is shown. The radius of this trajectory is $(r_2 - r_1)/2$. Two BSs are moving synchronously with constant velocity during their movement. Each BS broadcasts a message while moving. After that, nodes share their current status with BS telling whether these are in communication range or not. If a node receives message from two BSs, it replies with a data packet to any one of them (randomly). Nodes, which are not in communication range

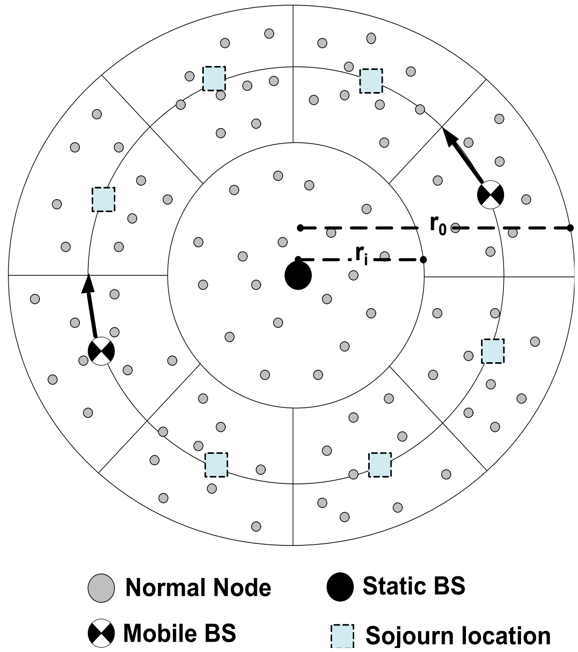


FIGURE 3.6: iAM-DisCNT: schematic

of any BS, switch to sleep mode. Whereas, nodes which come to communication range of any BS switch to active mode and start transmissions.

Outer BSs are named as (S_A) and (S_B). These BSs move in the circular trajectory and follow the circle equations that are given below for each moving BS. For S_A, the equations are:

$$x_A = R_A \cos(\theta) \tag{3.11}$$

$$y_A = R_A \sin(\theta) \tag{3.12}$$

For S_B, the equations are;

$$x_B = -R_B \cos(\theta) \tag{3.13}$$

$$y_B = -R_B \sin(\theta) \tag{3.14}$$

TABLE 3.1: Difference between AM-DisCNT and iAM-DisCNT

Scheme name	Clustering	CH selection probability	Sink Mobility
AM-DisCNT	Static clustering	Depends upon residual energy of a node	Static sink
iAM-DisCNT	Static clustering	Mobile sink receives data from nodes	One static sink + 2 mobile sinks

where, $0^o \leq \theta \leq 360^o$ and $R_A = R_B$.

3.4.3 Calculation of energy consumption

We develop the following set of mathematical equations to calculate the energy consumption of nodes in each segment.

Referring figure 3.6, if A_i is the area of inner region and A_0 is the area of outer region (consisting of 8 subregions) then:

$$A_i = \pi \ {r_i}^2 \tag{3.15}$$

and

$$A_0 = \pi \ ({r_0}^2 - {r_i}^2) \tag{3.16}$$

where r_i and r_0 are the radii of inner and outer circles, respectively. Similarly, the number of nodes in inner region and outer region are calculated as follows:

$$n_i = \rho_i \ \pi \ {r_i}^2 \tag{3.17}$$

$$n_0 = \rho_0 \ \pi \ ({r_0}^2 - {r_i}^2) \tag{3.18}$$

where ρ_i and ρ_0 are the node densities in inner and outer regions, respectively. So, the total number of nodes in the network area is calculated as follows:

$$N = \rho_0 \; \pi \; {r_0}^2 \; - \; \pi \; {r_i}^2 \; (\rho_0 \; - \; \rho_i) \tag{3.19}$$

Since the inner region nodes in both protocols; AM-DisCNT and iAM-DisCNT, consume same amount of transmit energy so we develop the following equations.

$$E^{i}_{tx} = \rho_i \; \pi \; {r_i}^2 \; (E_{elec} + \epsilon_{fs} d^2) \; k \tag{3.20}$$

where E_{elec} is the per bit electronic circuitry energy, ϵ_{fs} is the amplifier type, d is the communication distance between sender and receiver, and k is the packet size in bits.

Using similar approach, we calculate energy consumption for the outer region non-CH nodes of AM-DisCNT as follows:

$$E^{0,AM-DisCNT}_{tx,\; non-CH} = (\pi \; \rho_0 \; ({r_0}^2 - {r_i}^2) - 8) \times (E_{elec} + \epsilon_{fs} d^2) \; k \tag{3.21}$$

Transmit energy of the CHs of AM-DisCNT is calculated as follows:

$$E^{0,AM-DisCNT}_{tx,\; CHs} = 8 \; (E_{elec} + \epsilon_{fs} d^2) \; k \tag{3.22}$$

Energy consumption of CHs in AM-DisCNT while gathering data is calculated as:

$$E^{0,AM-DisCNT}_{da,\; CHs} = 8 \; (E_{elec} + E_{da} + \epsilon_{fs} d^2) \; k \tag{3.23}$$

where E_{da} is the per bit data aggregation energy.

In iAM-DisCNT, none of the nodes are selected as CHs from the outer region. So these nodes only consume transmission energy which is calculated as follows:

$$E_{tx}^{0,iAM-DisCNT} = (\pi\ \rho_0\ ({r_0}^2 - {r_i}^2)) \times (E_{elec} + \epsilon_{fs} d^2)\ k \tag{3.24}$$

From these calculations, we conclude that the energy consumption of outer region nodes of iAM-DisCNT is less than that of AM-DisCNT. However, energy consumption is minimized at the cost of mobile BSs.

3.4.4 Information flow maximization model

Let the WSN is a graph $G = (N, L, S)$; $|N| = n$ nodes, $|L| = l$ links and $|S| = k$ BSs such that $\exists(i, k) \in L$ if and only if the data of node i is intended for direct transmission towards BS. Hence, linear programming model for throughput maximization is as follows.

$$Max \sum_{r} l.q_i^k(r) \quad \forall\ \ r \in R \tag{3.25a}$$

$$\text{subject to: } C_1 : q_i^k - R_i^k t_k^m \leq 0 \quad \forall\ \ i \in N \ and \ k \in S \tag{3.25b}$$

$$C_2 : \lambda_i t_k^m \leq F_i^k \quad \forall\ \ i \in N \ and \ k \in S \tag{3.25c}$$

$$C_3 : t_k^m \leq t_{min} \quad \forall\ \ k \in S \tag{3.25d}$$

$$C_4 : E_i \leq E_0 \quad \forall\ \ i \in N \tag{3.25e}$$

where,

$$l = \begin{cases} 1 & \text{if } p_l \geq p_s \\ 0 & \text{if } p_l < p_s \end{cases} \tag{3.26}$$

The objective function in equation 3.25a is to maximize the information flow 'q' from node 'i' to BS 'k' during the current round 'r' belonging to the set of rounds 'R' throughout the network lifetime. This objective function depends on the link flag 'l' which depends on probability of given link 'p_l' such that if its value is $\geq$ the minimum required probability for successful transmission 'p_s' then the flag is raised else it is not. Constraint in equation 3.25b determines R_i^k as the upper bound on transmission rate of link $(i, k) \in L$ during the sojourn time 't' of BS 'k' at sojourn location '$m \in M$' as shown in figure 3.6. Similarly, constraint in equation 3.25c determines that the information generation rate 'λ' should not exceed the outgoing flow 'F' during sojourn time. Violation of C_1 and/or C_2 leads to loss of data which ultimately results in decreased data flow. Constraint in equation 3.25d provides explanation about the sojourn time (stay time at location m) of the BS that this interval should be at least equal to the minimum required time for successful data transmission. Alternatively, equation 3.25d indicates about the existence of tradeoff between delay and network lifetime. Equation 3.25e deals with energy constraint, i.e., each node is equipped with an energy source 'E_i' upper bounded by E_0. Nodes cease transmissions whenever their batteries are drained out so for data flow maximization the energy of nodes needs to be saved. In this regard, iAM-DisCNT puts a stop on node to node communication ($q_i^j = 0 \; and \; q_j^i = 0$) which is further facilitated by setting $q_k^i = 0$. This means that each node can only transmit data packets to BS, thereby not concerned with data packets reception from node(s) or BS(s) thus saving energy. Moreover, data flow is maximized with the introduction of two MSs and one static sink.

3.4.5 Packet drop minimization model

In addition to the information flow maximization, our second objective is to minimize the packet drop rate such that throughput of the network is maximized. In subject to this, we develop a linear programming based mathematical formulation as follows.

$$Min \sum_{r} PD(r) \quad \forall \;\; r \in R \tag{3.27a}$$

$$\text{subject to: } C_1 : n_s \rightarrow n_s^{opt} \tag{3.27b}$$

$$C_2 : d_{i,k} \rightarrow d_{i,k}^{min} \quad \forall \;\; i \in N \; and \; k \in S \tag{3.27c}$$

$$C_3 : Min \; I_{ch} \tag{3.27d}$$

$$C_4 : q_i^- + \lambda_i t \leq q_i^+ \quad \forall \;\; i \in N \tag{3.27e}$$

The objective function in equation 3.27a aims to minimize; $\sum_r PD(r)$, the total number of dropped packets. Constraint 3.27b states that the number of sojourn locations 'n_s' should approach its optimal value n_s^{opt}. Agreement with C_1 means proper cluster size which in turn means decreased contention for channel access at sojourn location(s). Thus, leading to decreased packet drop rate as rounds proceed. Similarly, constraint 3.27c focuses on the minimization of communication distance '$d_{i,k}$' to approach its minimum possible value $d_{i,k}^{min}$ whenever node 'i' is intended to communicate with BS 'k' at particular sojourn location. Violation of C_2 means low SNR value at the receiver end which causes increased packet drop rate. In addition, constraint 3.27d aims to minimize channel interference 'I_{ch}'; it includes both co-channel and adjacent channel interference. Incase of high channel interference, the packet drop rate would increase and vise versa. Finally, constraint 3.27e does not allow the incoming data flow at a given node 'q_i^-' plus the data generated by that node 'λ_i' during time span 't' to exceed its outgoing data flow limit 'q_i^+'. Violation of C_4 would lead to buffer overflow because arrival rate exceeds the packet handling capacity. In other words, violation of C_4 would lead to increased packet drop rate.

Graphical analysis: Let q_i^+ is varied between $0 - 2000$ bits, such that $\lambda_i t_k$ is

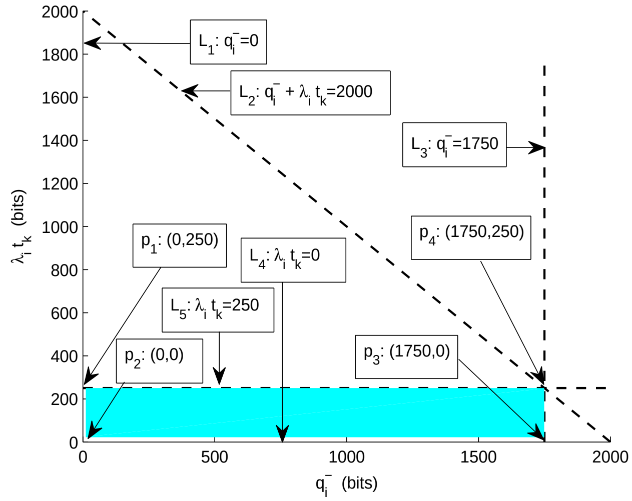


FIGURE 3.7: Feasible region

between $0 - 250$ bits and q_i^- is between $0 - 1750$ bits. Considering these values, the bounds for constraint in 3.27e can be re-written as follows:

$$0 \leq q_i^- + \lambda_i t_k \leq 2000 \quad \forall \ \ i \in N \tag{3.28a}$$

$$0 \leq q_i^- \leq 1750 \quad \forall \ \ i \in N \tag{3.28b}$$

$$0 \leq \lambda_i t_k \leq 250 \quad \forall \ \ i \in N \tag{3.28c}$$

In subject to the bounds provided by equations 3.28a, 3.28b and 3.28c, figure 3.7 shows the intersection of five lines (L_1, L_2, L_3, L_4 and L_5). As can be seen in this figure, the intersection results in a bounded region (which is colored cyan) as the feasible region. In this region, the set of all possible solutions lie. Other than this region, all other solutions are invalid. In order to verify the validity of our statement, let us test each vertex of the feasible region for valid solution.

at p_1: (0,250)=0+250=250 bits,

at p_2: (0,0)=0+0=0 bits,

at p_3: (1750,0)=1750+0=1750 bits, and at p_4: (1750,250)=1750+250=2000 bits.

Hence, it is proved that the set of all possible solutions that lie within the premises of feasible region are valid.

3.5 Simulation results

Simulations of iAM-DisCNT are performed in C based stimulater. In this section simulation results are discussed along with performance trade-offs.

3.5.1 Performance metrics - definitions

Following performance metrics are considered:

1. Network lifetime: It is the time period from the start of the network till the death of the last node in the field. It is measured in the unit of time (seconds). It is one of the most important parameter every network is supposed to have.
2. Throughput: It is the total number of packets successfully received at the BS. It excludes the packet sent by the sensor nodes in the field but dropped on their way to BS because of any reason. Its unit is packets/sec.
3. Packet drop: It is defined as the number of packets sent towards the BS, however, they are not received at BS. Number of packets dropped due to bad link quality. We considered random uniformed model [83] for packet dropped calculation, in which the probability of packet drop is set to 0.3.
4. Total energy consumption: It is defined as the total energy consumed by all the alive nodes. It is measured in Joules.
5. End-to-end delay: It is the total time taken by all packets to reach from source node to BS. It is also measured in seconds.

3.5.2 Performance metrics - discussions

In this section, we evaluate the performance of the proposed protocols. Twenty nodes are randomly deployed in the inner circle. For the formation of clusters outer circle is partitioned into eight equal regions. Each cluster contain equal number of nodes that is 10. Inner and outer circles have radius $20m$ and $35m$ respectively. The radius of BS trajectory is $27m$. Simulation parameters are shown in table 3.2, and average results with 90% confidence interval are shown and discussed in the upcoming subsections.

Table 3.2: Simulation parameters

Parameter	Value
N	100
R_1	27 m
R_2	100 m
E_0	0.5 J
ϵ_{fs}	10 $pJ/bit/m^2$
E_{elec}	50 nJ/bit

Fig. 3.8 shows that the stability period and network lifetime of the proposed protocols is greater than the existing protocols. AM-DisCNT's superior performance in comparison to LEACH and DEEC is due the minimization of communication distance and proper selection of CHs. iAM-DisCNT shows further improvement in stability period and network lifetime at the cost of multiple BSs (one static and two mobile). Furthermore, unlike LEACH and DEEC in proposed scheme there is fix number of CHs: one CH per region in the outer circle. This type of CHs' selection ensures data delivery from every part of network to BS. Thus, ensuring full area coverage.

The rate at which CHs are selected in the proposed as well as chosen existing routing protocols is shown in figure 3.9. This figure depicts that the selected CHs in LEACH routing protocol vary from 5 to 15 (per round) during initial

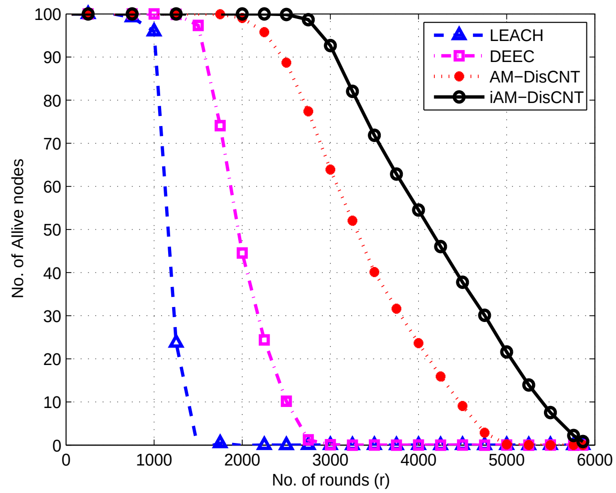


FIGURE 3.8: Stability period and network lifetime

rounds and then this rate drops to zero. Similar is the case with DEEC protocol, where the selected CHs fluctuate between 3 and 36 during initial rounds. Both of these protocols do not guarantee optimum number of CHs throughout the network lifetime. Fluctuation in CHs number is due to random selection criteria of these protocols. In response, this random number of selected CHs may lead to one of the two drawbacks: (i) the selected CHs are more than the required number of CHs, and (ii) the selected CHs are less than the required number of CHs. Alternatively, the first drawback means surplus energy consumption and the second drawback means large cluster size. Surplus energy consumption leads decreased network lifetime and large cluster size leads to more load on the selected CHs. AM-DisCNT routing protocol fixes both of these drawbacks by selecting one CH per round from each of the eight outer regions. iAM-DisCNT further extends the network lifetime by introducing mobile BSs.

From figure 3.10, we see that LEACH sends the smallest number of packets to BS as compared to DEEC, AM-DisCNT, and iAM-DisCNT. This is due to LEACH in which all nodes are homogenous. Selection based upon Such assumption makes low energy nodes as CHs which finally results in increased number of dead nodes.

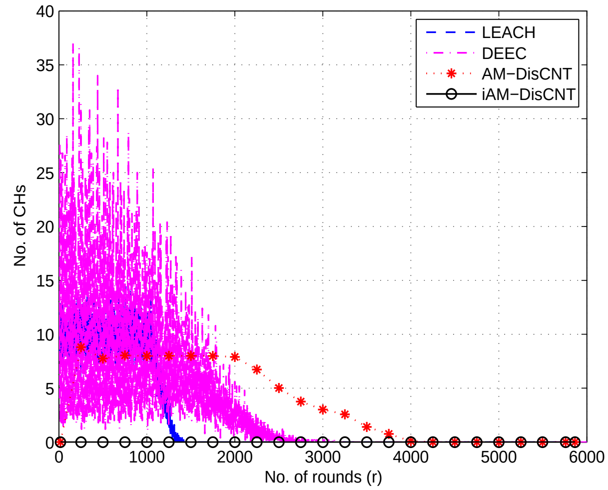


FIGURE 3.9: Rate of CH selection

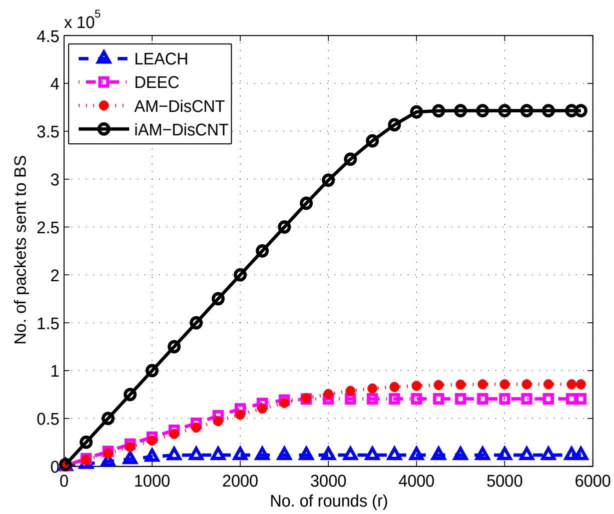


FIGURE 3.10: No. of packets sent to BS

DEEC performs better than LEACH because it selects CHs based on the ratio of residual energy of nodes and average energy of the network. This conserves energy and increases network lifetime, thus increases the number of packets sent to BS. The performance of DEEC and LEACH is not satisfactory because of varying cluster sizes. Farther nodes use more energy to send the sensed data and die quickly leaving some area un-monitored. AM-DisCNT outperforms LEACH, however, DEEC has batter throughput (number of packets sent to BS) due to greater number of nodes. On average, DEEC outperforms AM-DisCNT; two times out of five. Greater number of CHs implies larger number of packets sent to BS. This problem is catered in iAM-DisCNT by using one static and two mobile BSs. This approach increases the probability of direct communication between nodes and BS and less distance between nodes and BS reduces the energy consumption of nodes leading to maximized number of packets sent to BS.

During transmission of packets from source to destination through wireless channel, some transmitted packets may get dropped due to bad channel conditions. In order to calculate dropped packets, we use random uniformed model [76]. We set the probability of channel to be in bad status as 0.3 (30%). Figure 3.11 shows the number of successfully received packets at BS for the newly as well as selected existing routing protocols. iAM-DisCNT shows greater number of successfully received packets at BS as compared LEACH, DEEC and AM-DisCNT routing protocols.

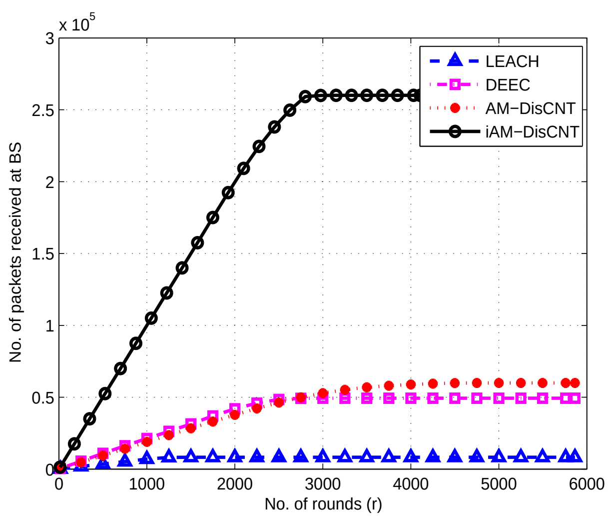


FIGURE 3.11: No. of packets received at BS

Figure 3.12 shows end-to-end delay comparison of iAM-DisCNT, AM-DisCNT, LEACH and DEEC. Greater end to end delay, in case of DEEC and LEACH

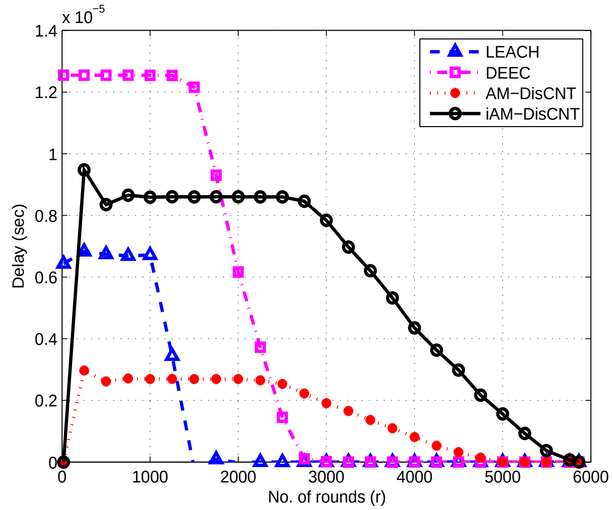


FIGURE 3.12: End to end delay

protocols is due to greater queuing and processing delays. Due to distant communication between sender and receiver, LEACH and DECC exhibit greater end to end delay. In AM-DisCNT, logical divisioning of the network area decreases the communication distance for the delivery of packets causing minimization of the propagation time, thereby, showing least end to end delay among the selected routing protocols. Introduction of mobile and static BSs, in iAM-DisCNT, increases the chances of direct communication with BS which decreases the propagation delay from nodes to their respective BSs to some extent. However, data packets delivery to final destination increases the overall propagation delay which alternatively increases the end to end delay.

3.5.3 Performance metrics - trade-offs:

In order to achieve a(some) desired objective(s), routing protocol pay its (their) cost in terms of other performance metric(s); trade-off(s). In this sub-section, we analyze the four simulated routing protocols (LEACH, DEEC, AM-DisCNT and iAM-DisCNT) in terms of performance trade-offs. We thus refer figure 3.8,3.11,3.12 and table 3.3; DEEC achieves higher energy efficiency as well as throughput as compared to LEACH, however, at the cost of high end-to-end delay. A major reason for this relatively higher end-to-end delay is distant communication. AM-DisCNT logically divides the network area to minimize the end-to-end delay that also leads to increased energy efficiency. This is obvious as the local clusters are more restricted, i.e., minimization of the communication distance.

Table 3.3: Comparative analysis of the selected routing protocols

Protocol	Node deployment	Sensor batteries	Control mechanism	Sink mobility	No. of sinks	Route processing	Network lifetime	Throughput	Delay
LEACH	Random	Homogeneous	Centralized	NIL	1	Proactive	+	++	++
DEEC	Random	Heterogeneous	Distributed	NIL	1	Proactive	+++	+++	++++
AM-DisCNT	Hybrid	Heterogeneous	Hybrid	Yes	1	Proactive	++++	+++	+
iAM-DisCNT	Hybrid	Heterogeneous	Hybrid	Yes	2	Proactive	+++++	++++	+++

Table 3.4: Comparative analysis of the selected routing protocols

Protocol	Achievement(s) made	Cost paid
LEACH	freedom in node deployment	network lifetime
DEEC	network lifetime and throughput	end-to-end delay
AM-DisCNT	end-to-end delay and network lifetime	freedom in node deployment
iAM-DisCNT	network lifetime and throughput	end-to-end delay and an additional MS

However, this achievement is made at the cost of restricted freedom at the time of node deployment (uniform random deployment of nodes). iAM-DisCNT further improves the network lifetime and throughput at the cost of an additional MS. Moreover, this protocol also pays the cost of somewhat increased end-to-end delay as compared to AM-DisCNT. All these trade-offs are summarized in table 3.4.

3.6 Chapter conclusion

We have proposed two energy efficient routing protocols for WSNs; AM-DisCNT and iAM-DisCNT. In the first one there is static clustering and selection of CH is based on maximum residual energy nodes. The second; iAM-DisCNT, has two mobile BSs that collect data directly from nodes. Mobile BSs follow a pre-defined trajectory, minimizing the communication distance. In addition to the two newly proposed protocols, graphical analysis of the proposed linear programming based mathematical models provides the bounds within which the set of all possible solutions lie. Simulation results show that AM-DisCNT has approx. 32% whereas, iAM-DisCNT has approx. 48% improved the stability period as compared to LEACH and DEEC routing protocols. Similarly, throughput of AM-DisCNT and iAM-DisCNT are improved approx. 16% and 80% respectively from compared schemes. Based on these results, we have also analyzed the four simulated routing protocols in terms performance trade-offs.

In next chapter, we have proposed another scheme that is reactive. First we consider the static clustering and selection of the CHs is based on residual energy.

Chapter 4

Sink mobility aware multi-hop scalable hybrid energy efficient protocols

4.1 Chapter summary

In this chapter, we propose two routing protocols for TWSNs; Hybrid Energy Efficient Reactive (HEER), and Multi-hop Hybrid Energy Efficient Reactive (MHEER) routing protocol. The main purpose of designing these protocols is to improve the network lifetime and particularly the stability period of the underlying network. In MHEER, the node with the maximum energy in a region becomes CH of that region for that particular round (or cycle) of time and the number of the CHs in each round remain the same. Along with stability and network lifetime we also calculated the confidence interval of all our results which helps us to visualize the possible deviation of our graphs from the mean value. Moreover, we implement sink mobility on HEER and MHEER. We refer them as HEER-SM and MHEER-SM. Simulation results show that HEER-SM and MHEER-SM yield better network lifetime and stability region as compared to its counterpart techniques.

4.2 Proposed protocols: HEER and MHEER

Since this research work is focused on the improvement of networks energy efficiency and reactive protocols are more energy efficient than the proactive ones, thereby, we have explored reactive protocols. In this section, we explain our proposed protocols HEER [77] and MHEER. A number of routing protocols have been proposed in the field of WSNs. Most of them involve clustering. However, not much attention has been devoted towards time critical applications. DEEC, being a proactive heterogeneous network protocol is not well suited for time critical applications. TEEN is a reactive protocol and it guarantees that the unstable region would be short in a homogenous network. This is due to the well distributed uniform energy consumption in TEEN. On the other hand, TEEN yields a large unstable region in a heterogenous network because the CH selection process becomes unstable and the nodes stay in idle state for most of the time. HEER chooses CHs on the basis of residual energies of the nodes. Because of its reactive nature, it reduces the number of transmissions and results in better network lifetime and stability region than TEEN and DEEC. On the other hand, MHEER yields better results in terms of lifetime and stability period as compared to HEER. The number of CHs in HEER are not fixed in every round. Whereas, MHEER uses static clustering. It also takes into account the maximum energy nodes at the start of each round for the CH selection. We explain both the proposed protocols in detail in the following sections.

4.2.1 HEER

As we have already explained, proactive protocols sense their environment and transmit data periodically. They consume energy continuously due to periodic transmissions. Main focus in proactive protocols is on increasing lifetime, throughput and to decrease energy consumption. In reactive protocols, a node senses the environment periodically but transmits data only when its value reaches the threshold value of the attribute. This technique reduces the number of transmissions. Reactive protocols are application dependent. Keeping in view the fact that data transmission consumes more energy than data sensing, throughput can be minimized or maximized as per application of the network. The throughput in reactive networks is inversely proportional to the network lifetime or its stability period. So, if the number of transmissions is less, it will result in extended stability period as well as network lifetime. However, if the current sensed value reaches the threshold value (absolute value) repeatedly then maximum number of transmissions will occur and nodes will die quickly.

In this section, we propose HEER, which improves the stable region for clustering hierarchy process for a reactive network in homogeneous and heterogeneous environment. Similar to DEEC, this protocol also takes into account the initial and residual energy of nodes for CH selection. When cluster formation is finished, the CH transmits two threshold values, i.e., HT and ST. The nodes sense their environment repeatedly and if a parameter from the attributes' set reaches its HT value, the node switches on its transmitter and transmits data. The Current Value (CV), on which first transmission occurs, is stored in an internal variable in the node called Sensed Value (SV). Now the nodes will again transmit the data to their respective CHs if:

$$CV - SV \geq ST \tag{4.1}$$

If the CV differs from SV by an amount equal to or greater than ST, only then the nodes will transmit their data. It results in reduced number of transmissions. Figure 4.1 shows different states of a cluster. The outermost circle in all the states is referred to as a cluster. Nodes sense their environment continuously until the parameter (CV) reaches its HT value. As CV reaches HT value, the nodes start sending their data to the CH as shown in the state–2. The CH receives, aggregates and then transmits this data to the BS. The CV on which first transmission occurs is stored in SV. The node then again starts sensing its environment as shown in state–3 until the CV differs from SV by an amount equal to or greater than ST. When this condition is again satisfied, the node again switches on its transmitter and sends data to the CH. This data is then transmitted to the BS by the CH as shown in state–4.

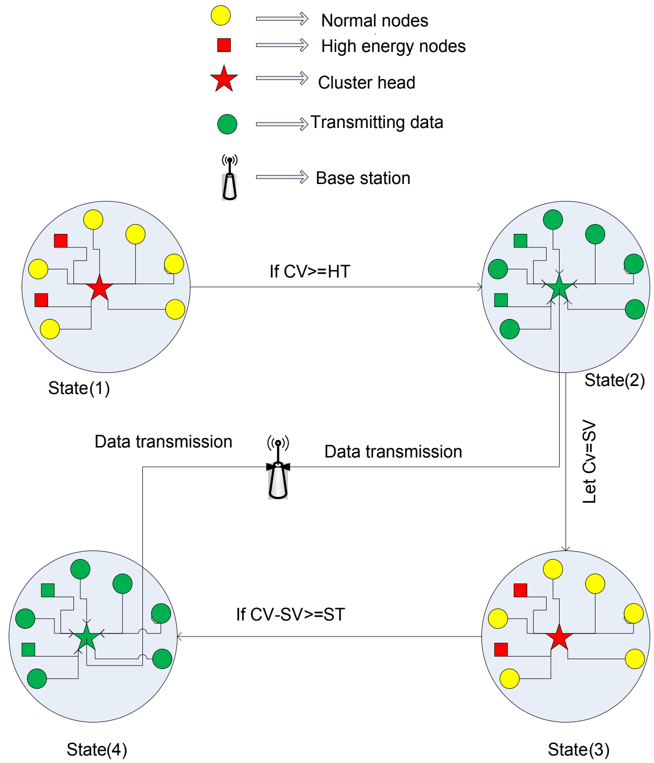


FIGURE 4.1: Idea figure for HEER from data sensing to data transmission for a cluster

4.2.2 MHEER

An efficient routing protocol is the one [77] which consumes minimum energy and also provides good coverage area. Minimum consumption of energy leads towards better network lifetime and particularly the stability period. Whereas, good coverage area is useful in getting the required information from the whole network area. The unattended areas are referred to as coverage holes. These coverage holes result in inefficient coverage area and those areas can not be monitored. So, the primary objective of a routing protocol is to achieve minimum energy utilization and full coverage area. Many researches have addressed such matters as in [44] - [46]. Different approaches can be used to solve this problem, one of which is the division of the network field area into sub-areas. In the proposed technique, we divide the network area into sub-areas as explained below.

We consider a WSN of area $100m \times 100m$. The whole area is divided into ten regions of equal area. Each one of these 10 regions acts like a cluster. The total number of nodes is 100. Each of the 10 regions contain 10 nodes randomly deployed in it. This division helps to improve the coverage area of the network and all areas are efficiently monitored. The network topology can be observed in the figure 4.2.

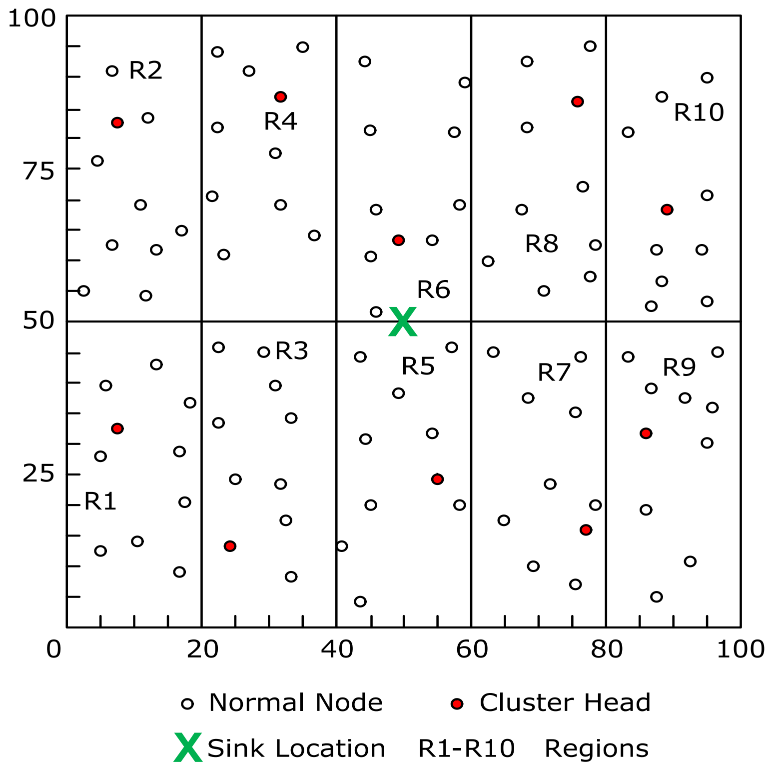


FIGURE 4.2: MHEER network topology

The network area is divided into 10 equal regions (i.e., R1–R10) as shown in figure 4.2. MHEER uses static clustering. Static clustering refers to the type of clustering in which clusters are predetermined and they do not change their number and size during any round. Only one CH is chosen from each region during every round. These CHs are responsible for the transmission of data to the BS. All nodes sense their data and send it to the CH of their region. The CH receives that data, aggregates it and then transmits it to the BS. The energy consumed during data transmission depends significantly on the distance between the CH and the BS.

Greater the distance, greater is the energy required to transmit that data to the BS. All CHs have their own distances from the BS which depend upon their region and their location in that region. A CH which is farther from the BS consumes more energy than the CH which is near the BS. MHEER uses multi-hoping technique to cop with this issue. According to this technique, the CHs which are farther from the BS do not send their data directly to the BS. Instead, they first send it to the CH which is nearer to them as compared to the BS. Those CHs then forward that data to the BS. According to the figure 4.2, CHs in region R1, R2, R9 and R10 do not send their data directly to the BS. They calculate their distance from the CHs of the adjacent regions and then send their data to the nearer one. In this way, a CH in region R1 first calculates its distance from the CHs of region R3 and R4, and then transmits its data to the BS via the CH which is near to it. Similarly, R2 calculates its distance from R3 and R4. Whereas, R9 and R10 calculate their distances from R7 and R8. This multi-hoping helps to improves the energy consumption efficiency and improves network lifetime and particularly the stability region.

As in any real case scenario, the number of packets received at the BS is never equal to the number of packets sent to the BS. This is because some packets are lost due to certain factors. Those factors may include interference, attenuation, noise, etc. That is why we implement the Uniform Random Distribution Model [78] for the calculation of packets drop. This makes MHEER more practical.

MHEER selects a node as the CH of its region if it has the maximum energy before the start of that round. Initially, all nodes have the same amount of energy and any node can become the CH for first round. A node is chosen randomly to become the CH of that region for the first round. All other nodes send their data to CH which receives that data, aggregates it and sends it to the BS. When the first round is completed, the amount of energy in each node is not the same anymore.

This is because the utilization of energy depends upon the distance between the node or CH which is transmitting and the CH or sink which is receiving. Distance is directly proportional to the energy consumption cost of a transmitting node. As distance for transmission and reception is different for different nodes, their energy consumption will also be different. For every next round, the CHs are selected on the basis of maximum energies. The node with the maximum energy in a region becomes the CH of that region for that particular round.

4.3 Sink mobility in HEER and MHEER: HEER-SM and MHEER-SM

In this section, we propose the application of sink mobility on HEER and MHEER and refer them as HEER-SM and MHEER-SM respectively. Sink mobility has been proved very effective in extending the network lifetime and particulary the stability region. We put greater emphasis on stability region because this is the region in which the data received at the BS is most reliable as every node is alive during this region. So, in terms of data integrity, stability region is very important. Multiple MSs would significantly prolong the network lifetime and maximize the throughput. However, the installation cost would also significantly increase. Thus, to prolong the network lifetime and maximize throughput while keeping the installation cost within a fairer limit, we have used only one MS.

Sink mobility refers to the movement of sink in the network to collect the data from the static nodes. These nodes can be either normal nodes or CHs, depending upon its application. Sink mobility is of two types; controlled and uncontrolled mobility. For the latter, the MS can move randomly in the network region. Whereas for the former, it can only move along the pre-defined trajectory. Controlled mobility can be implemented by two ways. In the first way, the sink can move in the

TABLE 4.1: Difference between HEER, MHEER, HEER-SM and MHEER-SM

Scheme name	Clustering type	Sink Mobility	Node deployment
HEER	Dynamic clustering	Static sink	Random
MHEER	Static clustering	Static sink	Random uniform in each cluster
HEER-SM	Dynamic Clustering	Mobile sink + CHs	Random
MHEER-SM	Static clustering	Mobile sink	Random uniform in each cluster

network on its predefined locations and these predefined locations can not be changed throughout the network lifetime. While according to the second way, the sink moves on its predefined locations but these locations are changed after every round. In this way, the sink moves in the controlled fashion, but its trajectory is changed after every round. In our technique, we implement the former method in which the sink locations are predefined and they are not changed throughout the network lifetime. These sink locations are also referred to as sojourn locations. The sink stops at these locations to collect the data from the nodes/CHs.

4.3.1 Network topology

The number of sinks is restricted to one. All nodes in the network are static i.e., they do not move. The sink moves between different regions in the network area under consideration. It stops at certain sojourn locations and collects the data from the nodes. In order to minimize the communication distance between nodes of a given sub-region and MS, the sojourn locations are chosen as the centre points of each sub-region. Figure 4.3 shows the network topology of our proposed sink mobility. The $\times$ marks show the sojourn locations in the network. The sink is mounted on an unmanned remote controlled vehicle and moves from one sojourn location to the next and collects data from the nodes at these sojourn locations. The nodes collect data and send it to their respective CHs. The MS stops at its sink stops and collects data from nodes or CHs.

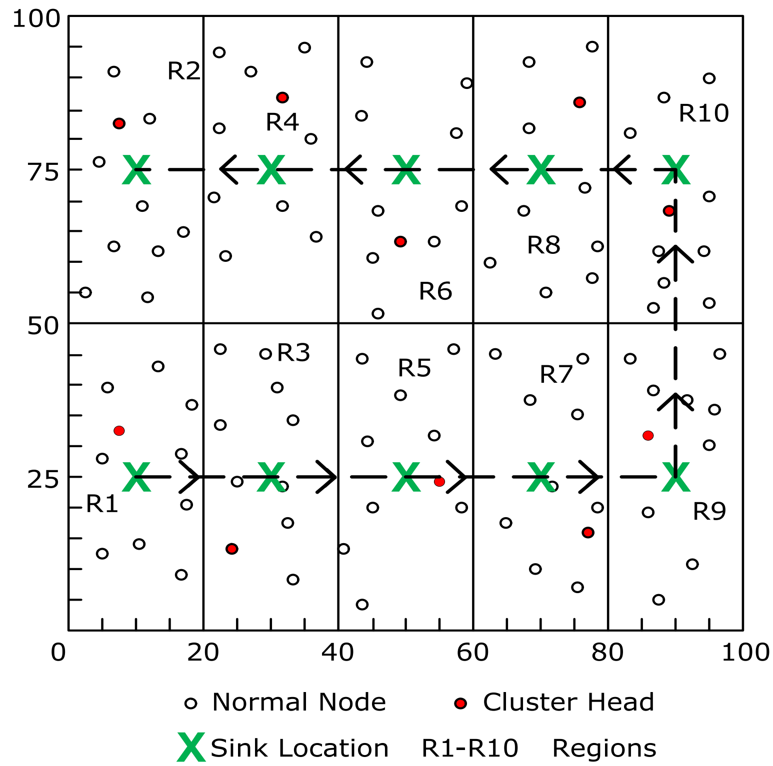


FIGURE 4.3: Sink mobility

The whole travel distance covered by the sink in the whole network lifetime should be bounded because a MS is usually driven by fuel or electricity. When a MS moves from one sink location to another, probability of data loss is high, so, the distance between two sink locations should be restricted. The transmission of data from nodes/CHs to sink only occurs when the sink is not moving i.e. sink is located at any sink location. Therefore, the sum of stop times in the MS tour should be maximized. There should be maximum number of stop locations of MS; as could be seen from figure 4.4.

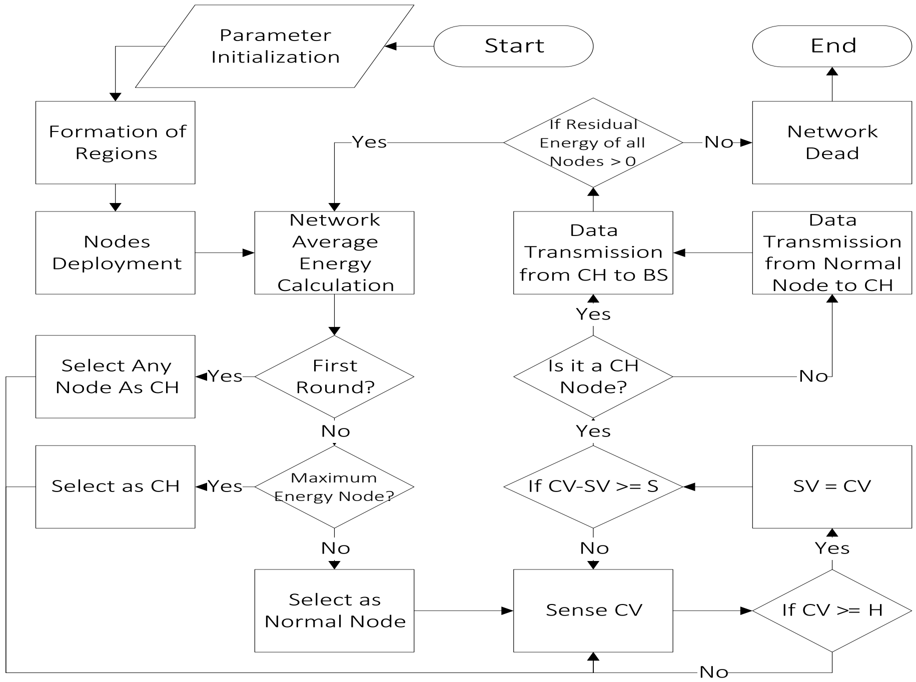


FIGURE 4.4: Flow chart of MHEER protocol

4.3.2 Clustering mechanism

In our model, a single sink moves around the network to collect the data from the nodes/CHs from its sink locations. These sink locations are predefined and do not change throughout the network lifetime.

In MHEER, the sink moves to each region and stops at its specific sojourn location to collect that data. As there are 10 regions, and the sink has to collect the data from all regions, so there are 10 sink stops predefined. These stops are located in the middle of each region. The CHs collect data from the nodes, aggregate it and send it to the sink whenever the sink comes to their region to collect the data. In case of HEER, the area is not not divided into sub-regions. But the sink locations for HEER are also the same as that for MHEER. The difference is that in MHEER, each region is predefined and each region has its own CH to transmit the data to the sink. So, when the sink arrives, the CH sends it data to it. Whereas in HEER, the regions are not predefined and clusters change their

Table 4.2: Simulation Parameters

Parameter	Value
Number of nodes	100, 500, 1000
Number of static sinks	1
Number of MSs	1
Static sink location	(50,50)
MS location	Specified trajectory (ref. figure 4.3)
Initial energy	0.5 J
Area	100m × 100m

shape and size. The number of CHs is not the same. So, each CH calculates its distance from its neighbouring sink locations and associates itself with the closest one. The normal nodes, in addition to calculating their distance from the CH, also calculate their distance from the sink location. These nodes then send their data to the one which is closer to them than the others. In this way, energy is quite efficiently consumed.

4.4 Experiments and discussions

In this section, we discuss the simulation results of our proposed protocols. Table 4.2 summarizes the simulation parameters used to validate the proposed protocols.

4.4.1 Performance metrics - definitions

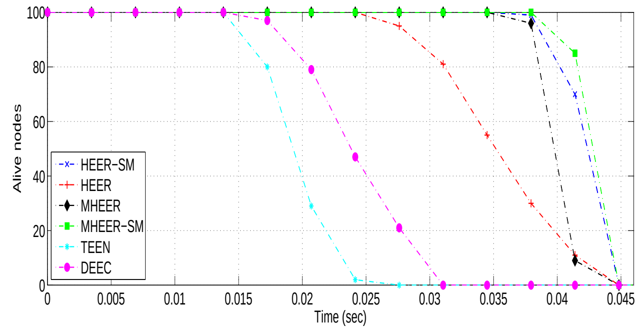
We consider the definitions given in chapter 3 in section 3.5.1.

4.4.2 Performance metrics - discussions

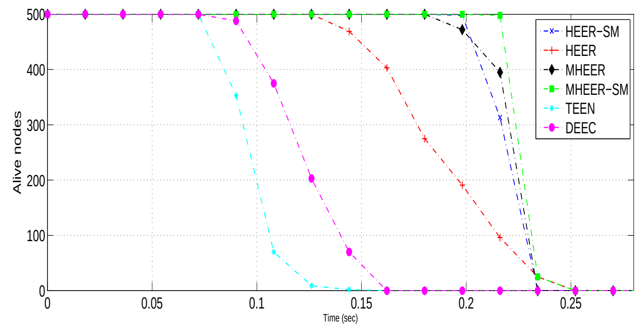
In this section, we discuss the performance parameters by which we measure, evaluate and then compare our proposed protocols with the existing counter part protocols. For the sake of fair comparison, we have assumed the soft and hard threshold ranges as in the selected protocol for comparison, i.e., TEEN. Similar reason holds about the initial energy of nodes.

4.4.2.1 Network lifetime

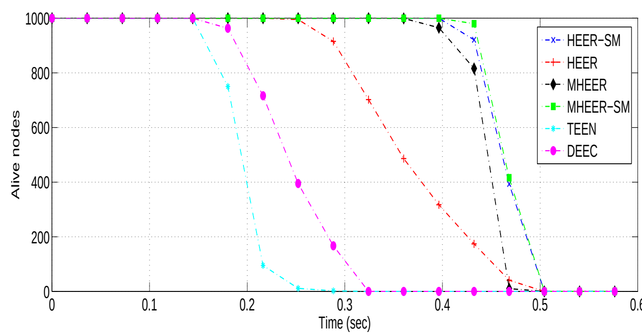
To understand the network life time, we first define the alive nodes. The nodes with sufficient energy to sense, process and then transmit the data to the neighbors, and/or BS or any other node in its transmission range, are generally referred to as alive nodes [77]. Generally, the lifetime of any network is depending upon the number of alive nodes (which in fact is depending upon the initial energy and consumption of energy). As per our assumption, even if a single alive node in the network is working, the network is assumed as alive. High energy consumption could result in short lifetime and vice versa. The efficient routing protocols generally result in the efficient consumption of energy which ultimately improves the network lifetime.



(a) Lifetime of Network for 100 Nodes



(b) Lifetime of Network for 500 Nodes



(c) Lifetime of Network for 1000 Nodes

FIGURE 4.5: Lifetime of network for different no. of nodes

TABLE 4.3: Dead nodes at different instants of time (for 100 nodes)

Protocol Name	First Node Dead at	Last Node Dead at	Dead Nodes			
			0.01 sec	0.02 sec	0.03 sec	0.04sec
HEER	0.024 sec	0.044 sec	0	0	15	81
HEER-SM	0.037 sec	0.044 sec	0	0	0	19
MHEER	0.0344 sec	0.044 sec	0	0	0	56
MHEER-SM	0.037 sec	0.044 sec	0	0	0	9
TEEN	0.0138 sec	0.027 sec	0	60	100	100
DEEC	0.013 sec	0.031 sec	0	17	94	100

In figure 4.5, we compare the network lifetime of TEEN, DEEC, HEER, MHEER, HEER-SM and MHEER-SM. We can see that MHEER-SM has the best lifetime as compared to the other protocols. Whereas, TEEN has the least network lifetime. This is because MHEER-SM has the same network topology as that of MHEER with the exception that MHEER-SM has MS. This MS moves to every region and collects data from the CH of each region. In this way, the distance between the CHs and sink reduces, which results in efficient consumption of energy. We can observe that HEER outperforms TEEN and DEEC. This is because HEER selects the CHs on the basis of their residual energies. The data is transmitted only when the threshold limit is achieved. It further reduces the number of transmissions and improves the network lifetime. MHEER on the other hand, outperforms HEER. This is because MHEER is based on multi-hoping and the distant CHs transmit their data via muti-hoping. In this way, the energy is efficiently consumed. MHEER has static clusters and each cluster has one CH and fixed a number of nodes. This helps in improving coverage area and coverage holes are reduced. HEER-SM and MHEER-SM perform better than HEER and MHEER because mobility helps to reduce the distance between the CHs and the sink. In this way, the network lifetime and stability region is further improved. Lifetime and nodes dying at frequent intervals is given in table 4.3.

4.4.2.2 Lifetime maximization model

Our proposed protocol models a WSN as a graph $G = \{\zeta \cup \zeta_0,\ \upsilon \cup \upsilon_0\}$, where ζ and ζ_0 is the set of sensors and sink locations respectively. $N =\mid \zeta \mid$ is the number of sensors and $N_0 =\mid \zeta_0 \mid$ is the number of sink sites. $\upsilon = \{\ \zeta \cup \zeta\ \}$ is the set of wireless links between sensors nodes and $\upsilon_0 = \{\ \zeta \cup \zeta_0\ \}$ is the set of wireless links between sensor nodes and sink locations. $\ell_{ic} \in \upsilon$ if the CH c is within the communication range ρ_i of node i, where $\forall i, c \in \zeta$. Similarly, $\ell_{ik} \in \upsilon_0$ if the sink location k is within the communication range of node i, and $\ell_{ck} \in \upsilon_0$ if the CH c is within the communication range of sink location k, where $\forall k \in \zeta_0$. α_i is the data generation rate of a node i and its value is same for all nodes. The sink speed is taken as infinity.

The sink has unlimited energy and there is no energy issue for sink. The residual time of the sink at each location is defined as τ_k. Nodes send their data only during this time. Nodes do not send their data whenever the sink is in motion. λ_{ic} is the amount of data from node i to CH c. λ_{ik} is the amount of data from node i to the sink location k. And λ_{ck} is the amount of data from CH c to the sink location k. $\sigma = 1$, if the sink is at the sink site of a region. e^T_{ic} is the energy required to transmit one unit data from node i to CH c. The energy dissipated for the transmission of one unit data from node i to sink location k is defined as e^T_{ik}. The amount of energy consumed for the reception of one unit data is given as e^R_{ci}. Since the objective function and its given constraints are mixed integer non-linear, we have chosen mixed integer nonlinear programming model.

$$Maximize\Bigg(X = \sum_r \sum_k \tau^r_k\Bigg) \tag{4.2a}$$

Subject to:

$$(\sum_r (e^T_{ck} \sum_{\ell_{ck} \in \upsilon_0} \lambda^r_{ck} + e^R_{jc} \sum_{\ell_{jc} \in \upsilon} \lambda^r_{jc}) \leq E_c, \omega^r_i = 1, \forall j, c \in \upsilon, \forall k \in \upsilon_0) \tag{4.2b}$$

$$(\sum_r (e^T_{ik} \sum_{\ell_{ik} \in \upsilon_0} \lambda^r_{ik} + e^T_{ic} \sum_{\ell_{ic} \in \upsilon} \lambda^r_{ic}) \leq E_i, \omega^r_i = 0, \forall i, c \in \upsilon, \forall k \in \upsilon_0) \tag{4.2c}$$

$$(\sum_i \sigma_{ic} = 0, \ iff \ d_{ic} \leq d_{ik}, \forall i, c \in \upsilon, \forall k \in \upsilon_0 \tag{4.2d}$$

$$(\tau_k > 0, \lambda_{ij} \geq 0, \forall k, i, j) \tag{4.2e}$$

$$(\forall i, j, c \in \upsilon, \forall k \in \upsilon_0) \tag{4.2f}$$

This model is a mixed integer nonlinear programming model. We explain each equation below:

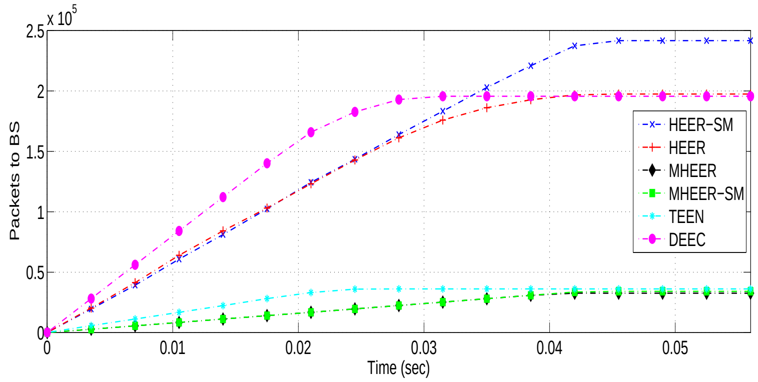
- **Objective function eq. 4.2a**: The objective function of this sink mobility model is to maximize the sojourn time of sink. The reason behind it is that the sink collects the data from the nodes or CHs only when it is at its sink location. It does not collect the data when it is in motion. So, as long as the sink stays at its sink location, it collects the data. In this way, improving the sojourn time will result in improving the network lifetime which is our main goal.
- **Energy constraint eqs. 4.2b and 4.2c**: According to these constraints, if a node is a CH, it receives the data from the nodes and sends that data to the sink. The energy consumed during this process should be less than that of the initial energy of the CH. Similarly, if a node is not a CH, then it will either send its data to the CH or to the sink depending upon their distance from that node. This consumption of energy should also be less than the initial energy of the node.
- **Flow constraint 4.2d**: This constraint shows that a node only sends its data to the CH if and only if the distance of the CH from the node is lesser than the distance between the sink and the node. If this distance is greater, then the node transmits its data directly to the sink instead of sending its data to the sink via the CH.
- **Pause time constraint 4.2e**: This constraint shows that the pause times of sink should be greater than zero because sink does not collect the data when it is in motion. It collects the data from the nodes or the CHs only when it is at its sink site. So, the sojourn time should be greater than zero to collect the data.

4.4.2.3 Throughput

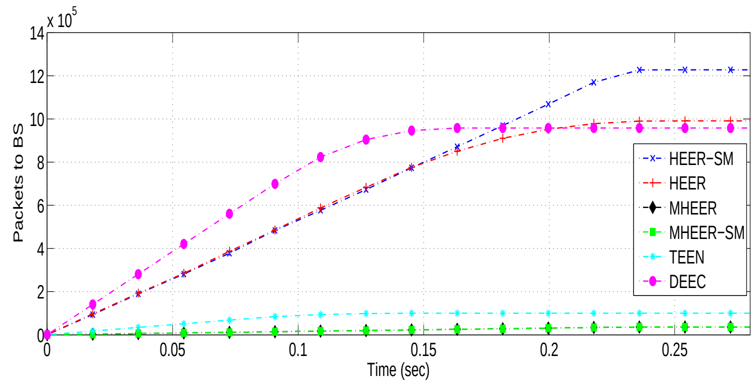
In this subsection, we discuss the number of packets sent to the BS. Figure 4.6 shows the total number of packets sent to BS in TEEN, DEEC, HEER, MHEER, HEER-SM and MHEER-SM. We know that the CH selection in HEER and HEER-SM is based on the probability assigned to the each node. This results in uneven number of CHs in each time round. As the number of CHs in each time round is not the same, the number of packets sent to the BS per time round is also not fixed. The number of packets sent to the BS varies in every time round. As the probability of CHs per time round in HEER and HEER-SM is 0.1 (i.e, same as in DEEC), the number of CHs in every time round should be 10. So the number of packets sent to the BS should also be 10. But the number of CHs does not remain fixed. As a result, the number of packets sent to BS is also not the same.
In case of MHEER and MHEER-SM, the selection of CHs is based on the maximum residual energy of a node in its region. As their are 10 regions and every region has 1 CH in each time round, the number of CHs in each time round is also 10. Each CH is responsible for sending its data to the BS. So, packets sent to the BS in every time round is also 10.

4.4.2.4 Data gathering maximization model

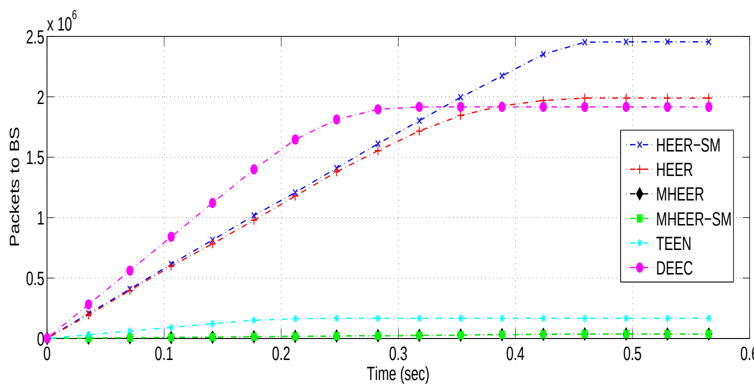
We also define a new model for the data gathering. In this model, we maximize the data gathering at the sink which results in maximized throughput. Maximum throughput leads to the conclusion that maximum data is gathered at the sink. This total data gathering λ_k at the sink site k can be defined as the sum of the data transmitted by the nodes and the CHs to the sink site. τ_{min} is the minimum sojourn time for which sink stays at site k. $\aleph$ is the total number of regions. It can be given by the following equation:



(a) Throughput of Network for 100 Nodes



(b) Throughput of Network for 500 Nodes



(c) Throughput of Network for 1000 Nodes

FIGURE 4.6: Packets sent to BS

$$\lambda_k = \sum_r \left(\sum_{\ell_{ik} \in \upsilon_0} \lambda_{ik}^r + \sum_{\ell_{ck} \in \upsilon_0} \lambda_{ck}^r \right), \forall i, c \in \upsilon, \forall k \in \upsilon_0 \tag{4.3}$$

This is also a MILP model:

$$Maximize\left(\lambda_k \right) \tag{4.4a}$$

subject to:

$$\tau_k^r \geq \tau_{min}, \forall k \in \upsilon_0, \forall r \tag{4.4b}$$

$$\mid \zeta_0 \mid = \frac{x_{lim} \times S}{\aleph},\ where\ S_{max} \geq S \geq 1 \tag{4.4c}$$

$$\mid \zeta_0 \mid = \frac{y_{lim} \times S}{\aleph},\ where\ S_{max} \geq S \geq 1 \tag{4.4d}$$

- **Objective function eq. 4.4a**: We maximize the data gathering at the sink which results in maximized throughput. Maximum throughput leads to the conclusion that maximum data is gathered at the sink. This total data gathering λ_k at the sink site k can be defined as the sum of the data transmitted by the nodes and the CHs to the sink site.
- **Sojourn time constraint eqs. 4.4b and 4.4c**: According to this constraint, increasing the sojourn time increases the amount of data gathering. This is because greater the time the sink stays at its sink location, greater is the time nodes and CHs get to send their data to the sink. So, a sink should stay for more time at its sink location than its least possible sojourn limit. This results in maximum data gathering.
- **Sink locations constraint eq. 4.4d**: This constraint discusses the number of sink sites. Greater the number of sink sites, greater is the amount of data gathered. So if a sink stops at more locations, it gathers more data than the

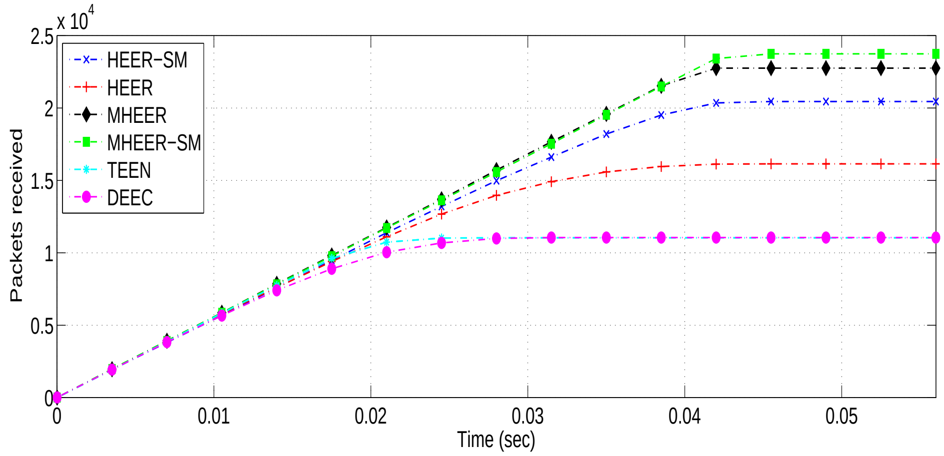
sink which stays at few locations. According to this constraint, the number of sink locations should be according to the network area and the number of regions in it. So, the number of sink sites can be determined by using the maximum limits of network's length x, width y and the number of regions.

4.4.2.5 Packet drop

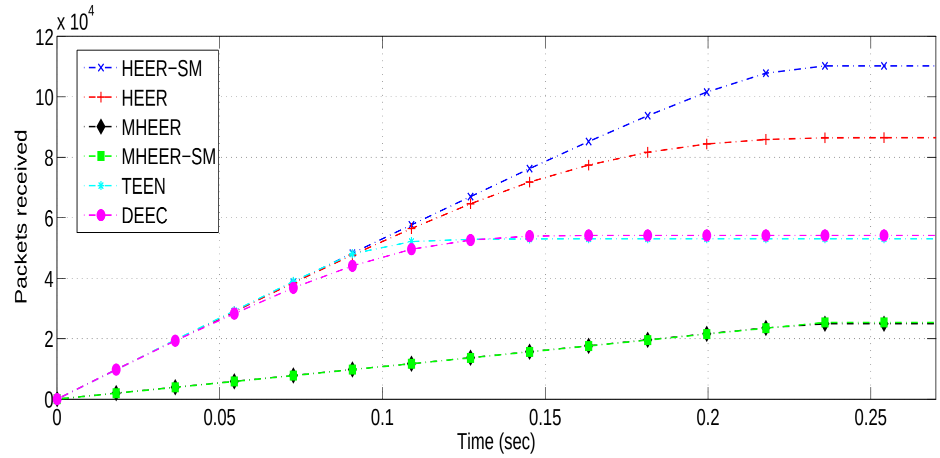
Packet drop can be defined as number of total packets sent minus the total number of packets received. Interflow and intra flow interferences, congestion, path loss, attenuation, noise, etc. could be the reasons for the packet drops. In our proposed techniques, we have used the uniform random distribution to calculate the number of dropped packets. We assume that it makes our protocol relatively robust as compared to the counter part schemes. We use 0.3 as the packet drop probability value from random uniform model [81]. Which means during every time round, a packet has a probability of 30% to be dropped.
Figures 4.6 and 4.7 show the total number of packets transmitted in the network and number of packets successively received only at the BS, respectively. From the figures it can be observed that total number of packets received at the BS is remarkably less than the total number of packets sent in the whole network

4.4.2.6 Energy consumption

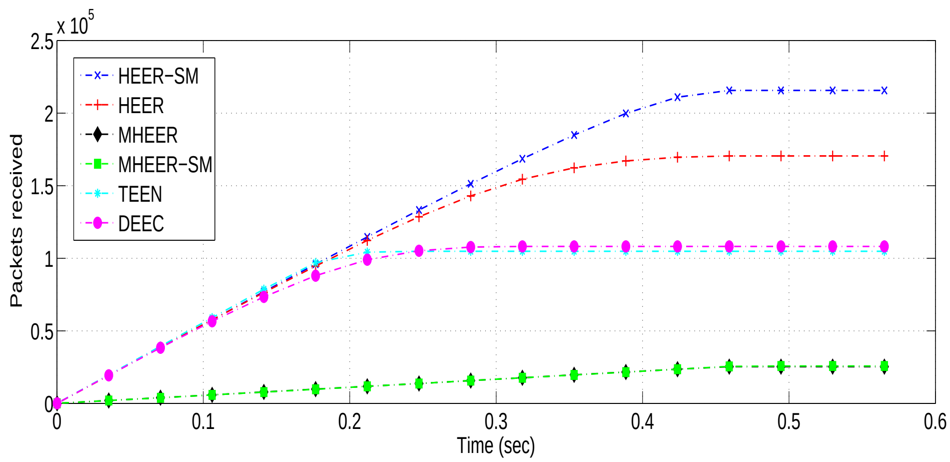
In this section, total energy consumption analysis is presented. Total energy includes the energy required for transmission, reception, and aggregation. Energy consumption of the network is inversely proportional to the network lifetime. From figure 4.5 and 4.8 it is obvious that shorter network lifetime results in greater energy consumption. Figure 4.8 compares the energy consumption of HEER, HEER-SM, MHEER, MHEER-SM, TEEN and DEEC. In the beginning, TEEN



(a) Total No. of Packets received successfully for 100 Nodes

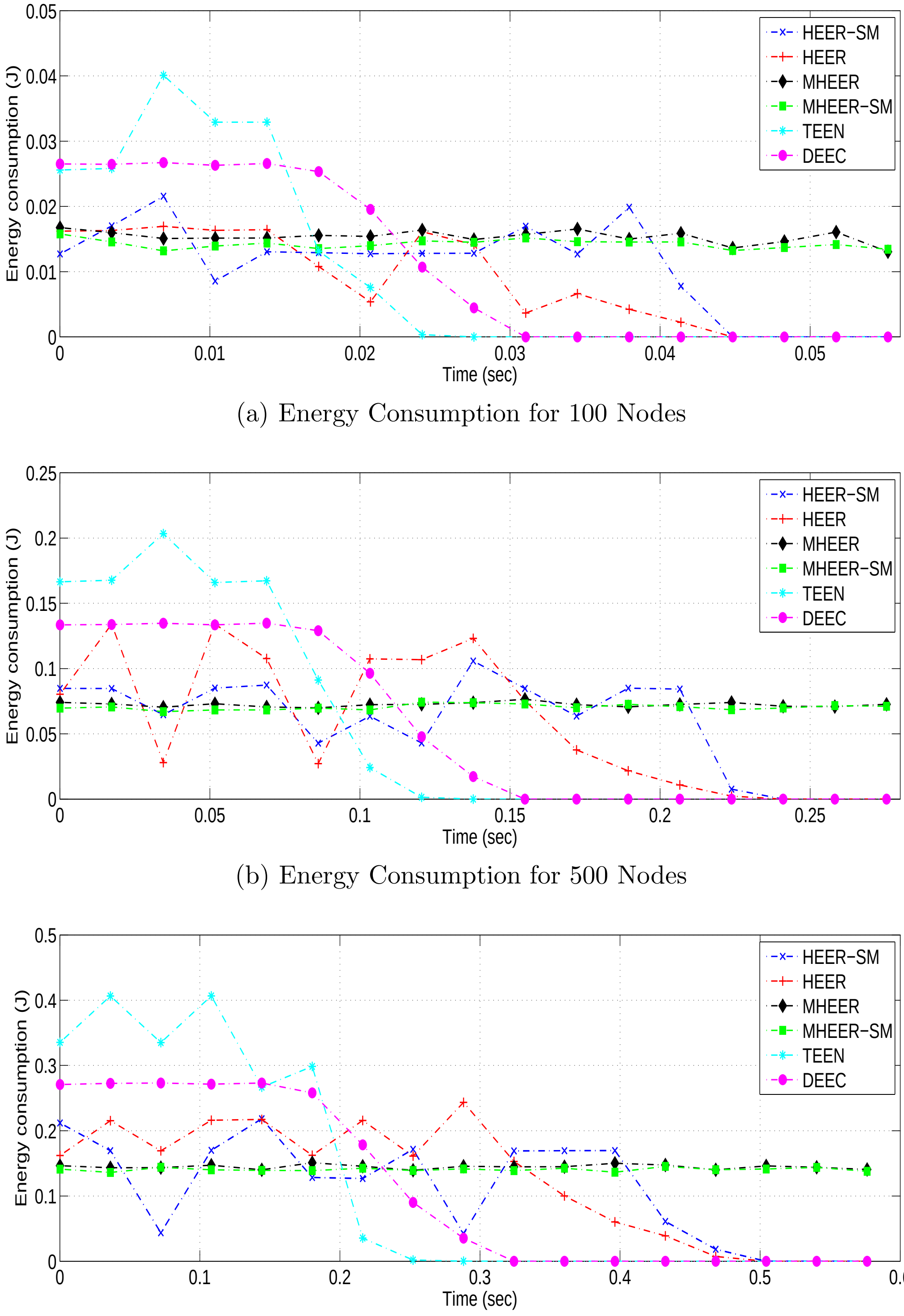


(b) Total No. of Packets received successfully for 500 Nodes



(c) Total No. of Packets received successfully for 1000 Nodes

FIGURE 4.7: Packet received successfully at the BS for 100, 500, and 1000 nodes



(a) Energy Consumption for 100 Nodes

(b) Energy Consumption for 500 Nodes

(c) Energy Consumption for 1000 Nodes

Figure 4.8: Energy consumption of the network for 100, 500, and 1000 nodes

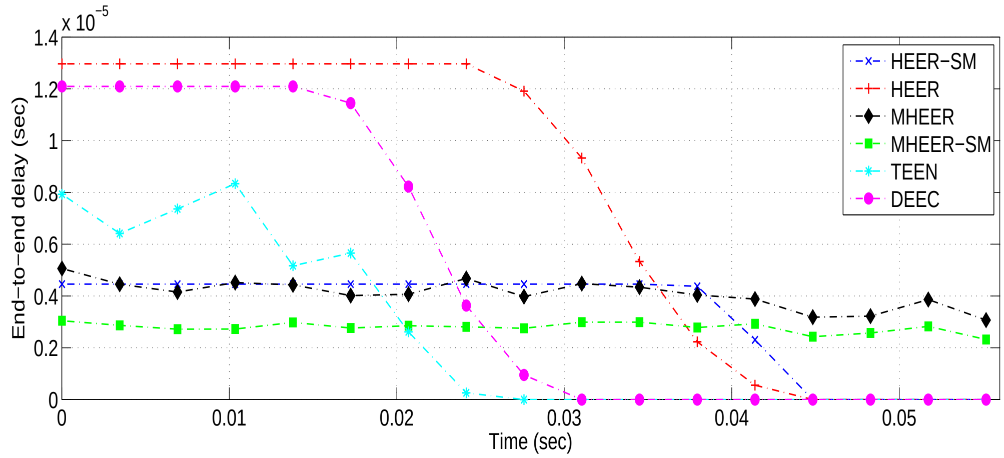
and DEEC have maximum energy consumption as compared to remaining protocol plots. DEEC being proactive protocol consumes more energy because of periodic transmissions and addition of advanced nodes which adds to total energy consumption count.

TEEN being reactive protocol consumes more energy among all reactive protocols because of random selection of CH and dies out faster. HEER is also a reactive protocol, however it takes into account residual and initial energy of nodes in CH selection process. Therefore, it has better energy consumption because of load balancing as compared to TEEN and DEEC. Although, stable region of HEER is more than TEEN and DEEC (figure 4.5), fluctuations in plots of HEER is due to its reactive nature. Protocol may have few or many transmissions in any particular time round. The CH selection is dynamic in HEER, therefore it has more energy consumption than MHEER and MHEER-SM. In dynamic CH selection process sometimes CH is far from BS and more transmission energy is consumed. MHEER consumes less energy and shows better network lifetime because of static clustering and non-distant transmissions from CH to BS. In case CH is far from BS, it transmits data to nearest CH instead of sending it to BS.

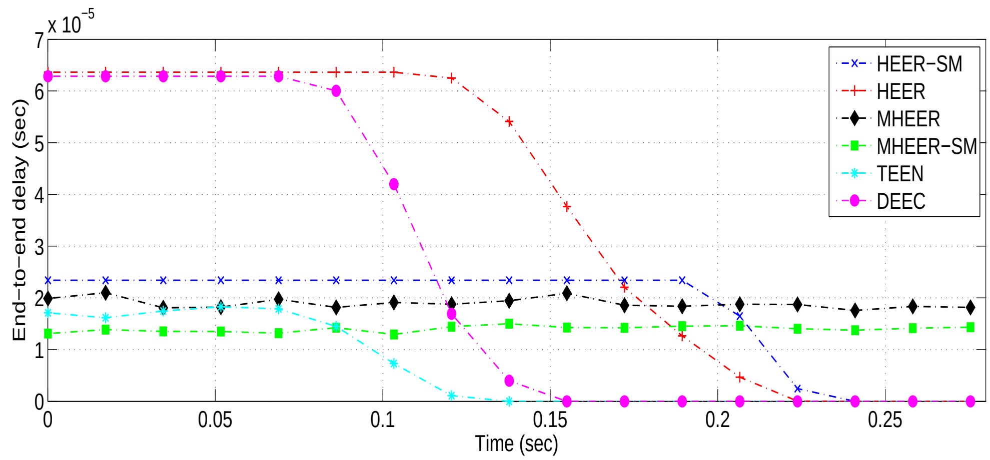
The introduction of MS in HEER-SM yields less energy consumption because sink may be more closer than CH or BS to receive data. Hence, nodes or CH do not do distant transmissions. However, sink mobility in MHEER has very little impact on energy consumption and network lifetime because the static clustering architecture of MHEER is enough to achieve such lifetime with the current mobility pattern of sink.

4.4.2.7 Delay

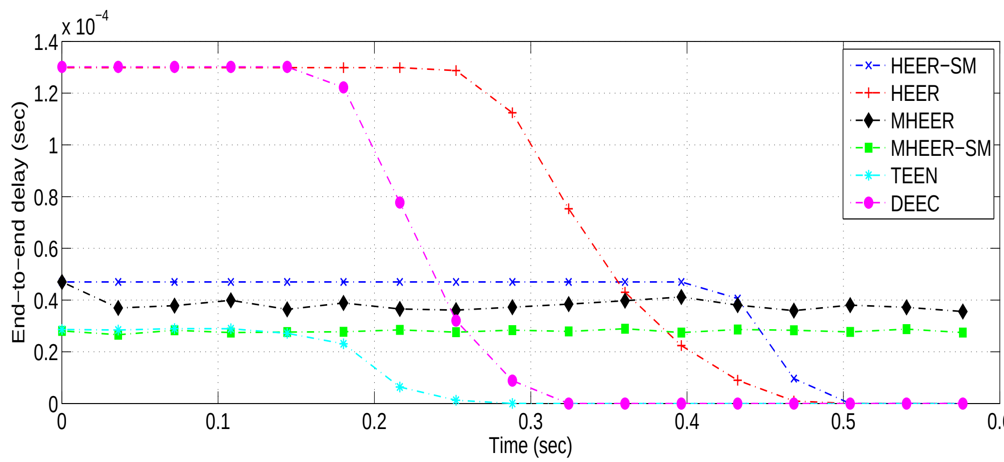
Figure 4.9 shows the end-to-end delay of the network. This delay includes the time required by all the alive nodes to transmit data to CH and from CH to BS.



(a) End-to-end Delay of the Network for 100 Nodes



(b) End-to-end Delay of the Network for 500 Nodes



(c) End-to-end Delay of the Network for 1000 Nodes

FIGURE 4.9: End-to-end delay of the network for 100, 500, and 1000 nodes

From figure 4.9, it can be seen that sink mobility improves delay performance. MHEER-SM has 39.8% less delay as compared to MHEER and results are even better in HEER-SM with 65% less delay in comparison to HEER. The improvement in delay performance is because of availability of sink in close vicinity after frequent intervals. Nodes, instead of transmitting data to CH and then CH takes another few seconds to transmit data to BS, transmit directly to MS. MHEER chooses maximum energy node as a CH which then transmit data to BS. CH can be at any location in the particular region and may not be nearest to all the cluster members in that region. However, in MHEER-SM the sojourn locations of MS are almost in the centre of every region that makes it feasible for all the cluster members and also CHs to transmit data with minimum delay and energy when MS is there.

Delay difference in HEER and DEEC is small in the beginning because both are following the same CH selection criteria, however, it increases later on because of difference in lifetime of both protocols. HEER has many alive nodes when DEEC dies out completely (ref figure 4.5).

Another observation from figure 4.9 is that static clustering protocols like MHEER and MHEER-SM have less delay as compared to dynamic clustering protocols like TEEN, DEEC, HEER, HEER-SM. The location of CHs in case of dynamic clustering is not fixed. CH and cluster members may be too close or too far form BS and CH respectively. In addition, number of CH is not fixed. Therefore, there may be less than optimal number of CH in any particular time round that leads to unbalanced regions. Nodes and CH, as a result do too many distant transmissions, thus add more delay.

4.4.3 Performance metric - trade-offs

In our scheme of MHEER, improvement in end-to-end delay is achieved at the cost of frequent transmissions due to packet loss whereas in MHEER-SM, the end-to-end delay is achieved at the cost of greater energy consumption. The end-to-end delay of the network in MHEER and MHEER-SM is improved compared to HEER and HEER-SM. The improvement in delay performance is because of availability of sink in close vicinity after frequent intervals. Instead of transmitting data to CH and then CH forwards data to base station after some time delay, nodes transmit data directly to MS.

In MHEER-SM, the sojourn locations of mobile station are almost in the center of every region that makes it feasible for all the cluster members and also CHs to transmit data with minimum delay when MS is there. Delay difference in HEER and DEEC is small in the beginning because both are following the same CH selection criteria; however, it increases later on because of difference in lifetime of both protocols. In MHEER and MHEER-SM, the stability period is improved because of the same network topology in both schemes with the exception that MHEER-SM has MS. This MS moves to every region and collects data from the CH of each region. In this way, the distance between the CHs and sink reduces, which results in efficient energy consumption. The stability period of MHEER is improved but at the cost of redundant transmissions due to packet loss at the sink.

Table 4.4: Performance trade-offs made by the protocols

Protocol	Achieved Parameter	References	Compromised Parameter	References
HEER	End-to-end delay improves	Figure 4.9	Throughput	Figure 4.6
MHEER	End-to-end delay improves	Figure 4.9	Frequent transmissions due to packet loss	Figure 4.7
HEER-SM	End-to-end delay improves	Figure 4.9	Energy consumption	Figure 4.8
MHEER-SM	End-to-end delay improves	Figure 4.9	Energy consumption	Figure 4.8
HEER	Stability period extends	Figure 4.5	End-to-end delay	Figure 4.9
MHEER	Stability period extends	Figure 4.5	Redundant transmissions due to packet loss	Figure 4.7
HEER-SM	Stability period extends	Figure 4.5	Greater energy consumption	Figure 4.8
MHEER-SM	Stability period extends	Figure 4.5	Throughput	Figure 4.6
HEER	Lifetime extends	Figure 4.5	End-to-end delay and energy consumption	Figures 4.8, 4.9
MHEER	Lifetime extends	Figure 4.5	Throughput	Figure 4.6
HEER-SM	Lifetime extends	Figure 4.5	End-to-end delay	Figure 4.9
MHEER-SM	Lifetime extends	Figure 4.5	Throughput	Figure 4.6

The stability period of MHEER-SM 4.5 is improved but at the cost of the network throughput. MHEER has static clusters and each cluster has one CH and fixed a number of nodes. This helps in improving coverage area and coverage holes are reduced.

HEER-SM and MHEER-SM perform better than HEER and MHEER because mobility helps to reduce the distance between the CHs and the sink. In this way, the network lifetime and stability region is further improved. Fluctuations in plots of HEER are due to its reactive nature. Protocol may have few or many transmissions in any particular time round. CH selection is dynamic in HEER, therefore it has more energy consumption than MHEER and MHEER-SM. In dynamic selection process, CH may be far from BS and more transmission energy is consumed. MHEER consumes less energy and shows better network lifetime because of static clustering and non-distant transmissions from CH to BS. In case CH is far from BS, it transmits data to nearest CH instead of sending it to BS.

In MHEER and MHEER-SM, network life-time is improved at the cost of net throughput of the network. The drop in network life-time in MHEER and MHEER-SM is much less than that of other schemes. In HEER and HEER-SM, network life-time is improved at the cost of end-to-end delay of the network and energy consumption. HEER improves the stable region for clustering hierarchy process for a reactive network in homogeneous and heterogeneous environment. The nodes sense their environment repeatedly and if a parameter from the attributes set reaches its HT value, the node switches on its transmitter and transmits data. In case of HEER, the area is not divided into sub-regions. But the sink locations for HEER are also the same as that for MHEER. The difference is that in MHEER, each region is predefined and each region has its own CH to transmit the data to the sink. Whereas is HEER, the regions are not predefined and clusters change their shape and size.

4.5 Chapter conclusion

In the proposed two scalable routing protocols; HEER, and MHEER, the selection of CHs is based upon the residual energy of the nodes. Fix number of CHs (only in MHEER) are selected in each cycle of protocol operation. Because of HEER's reactive nature, it reduces the number of transmissions and results in better network lifetime and stability region than TEEN and DEEC. Simulation results show that HEER-SM has approx. 38%, MHEER has approx. 40% and MHEER-SM has approx. 46% better stability period than HEER. Moreover HEER-SM and MHEER-SM yield better network lifetime and stability region as compared to its counterpart techniques.

In next chapter, we consider a four level heterogenous network. Where first we consider clustering, CHs are selected on the bases of residual energy and average energy of the network.

Chapter 5

Sink mobility aware energy efficient network integrated super heterogeneous protocol for WSNs

5.1 Chapter summary

In this chapter, we propose Balanced Energy Efficient Network Integrated Super Heterogenous (BEENISH), improved BEENISH (iBEENISH), Mobile BEENISH (MBEENISH) and improved Mobile BEENISH (iMBEENISH) protocols for heterogeneous WSNs. BEENISH considers four energy levels of nodes and selects CHs on the base of residual energy levels of nodes and average energy level of the network. Whereas, iBEENISH dynamically varies the CHs selection probability in an efficient manner leading to increased network lifetime. We also present a mathematical sink mobility model and validate this model by implementing it in BEENISH (resulting in MBEENISH) and iBEENISH (resulting in iMBEENISH). Finally, simulation results show that BEENISH, MBEENISH, iBEENISH and iMBEENISH protocols outperform contemporary protocols in terms of stability period, network lifetime and throughput.

5.2 Four level heterogeneous WSN model

A WSN can have nodes with different initial energies. Such kind of network is heterogeneous where initial energies of nodes are different. In our proposed scheme, we consider four different energy levels of nodes. On the bases of their energy we define them normal, advanced, super and ultra super. Where, normal nodes' energy is E_0, advanced nodes are of fraction m of normal nodes in the network and their energy is a times more than that of the normal ones i.e., $E_0(1 + a)$. Super nodes have greater energy as compared to the advanced nodes and they are of fraction m_0 of normal nodes with energy b times greater than as compared to normal nodes; $E_0(1+b)$. Similarly, ultra super nodes are of fraction m_1 of normal nodes with u times more energy than normal nodes; $E_0(1 + u)$. Total number of ultra super nodes presented in the network are calculated as follows:

$$Total\_Num_{ultra\_super} = Nm_1 \tag{5.1}$$

where, N is the total number of nodes in the network. Super nodes in the network are calculated as:

$$Total\_Num_{super} = Nm_0 \tag{5.2}$$

Advanced nodes in the network are computed by:

$$Total\_Num_{advanced} = Nm \tag{5.3}$$

Whereas, normal nodes are calculated as follows:

$$Total\_Num_{normal} = N(1 - m_1 - m_0 - m) \tag{5.4}$$

Initial energy of the ultra super nodes is calculated as follows:

$$E_{ultra\_super} = Total_{ultra\_super} \times E_0(1 + u) = Nm_1E_0(1 + u) \tag{5.5}$$

Initial energy of the super nodes is calculated as follows:

$$E_{super} = Total_{super} \times E_0(1 + b) = Nm_0E_0(1 + b) \tag{5.6}$$

The total initial energy of all advanced nodes is computed by:

$$E_{advanced} = Total_{advanced} \times E_0(1 + a) = NmE_0(1 + a) \tag{5.7}$$

Initial energy of the normal nodes is calculated as follows:

$$E_{normal} = Total_{normal} \times E_0 = N(1 - m_1 - m_0 - m)E_0 \tag{5.8}$$

Initial energy of the heterogenous network is computed by adding the energies of normal, advanced, super, and ultra supers nodes. The total initial energy is given in equation (9) and equation (10) as follows:

$$E_{total} = E_{ultra\_super} + E_{super} + E_{advanced} + E_{normal} \tag{5.9}$$

$$E_{total} = Nm_1E_0(1 + u) + Nm_0E_0(1 + b) + NmE_0(1 + a) + N(1 - m_1 - m_0 - m)E_0 \tag{5.10}$$

As compared to the homogenous network with initial energy E_0 our proposed heterogeneous WSN contains $Nm_1(1 + u) + Nm_0(1 + b) + Nm(1 + a) + N(1 - m_1 - m_0 - m)$ times more energy. Both networks have equal number of nodes. Figure 5.1 presents the network model of BEENISH.

When network starts operation, nodes consume different amount of energy for transmission depending upon the distance. Moreover, as compared to the nodes in the cluster, CH has more load of transmission, as it receives the data from member nodes and sends it to BS. In this way, CHs consume more energy. After some time, the residual energy of nodes present in the network may vary. We conclude that after certain time (rounds) a homogenous system becomes heterogenous because of difference in residual energy of nodes.

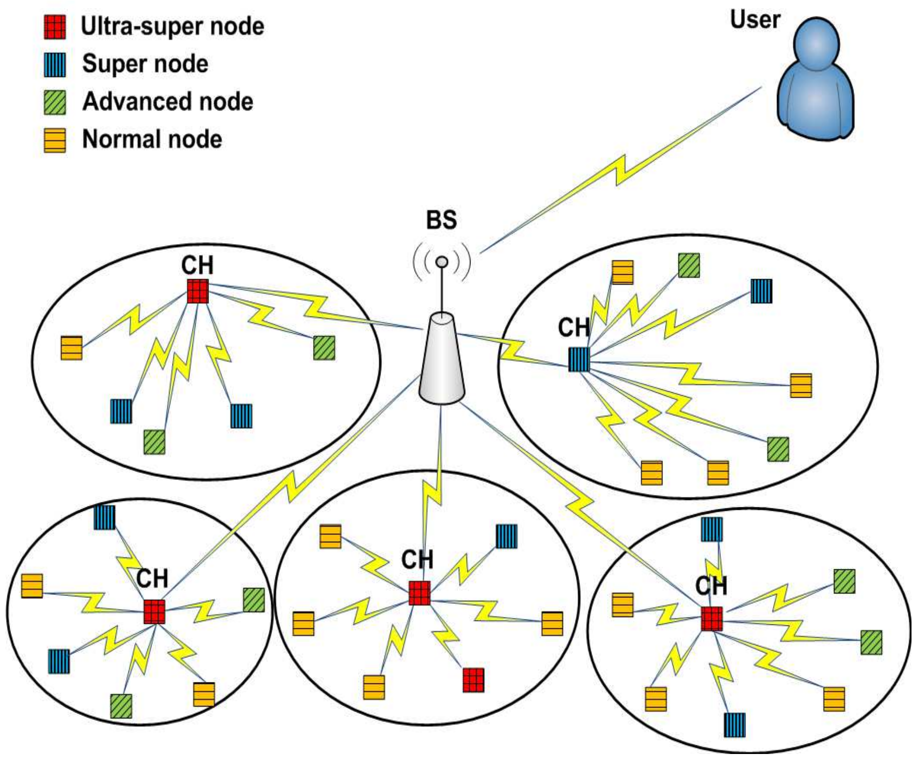


FIGURE 5.1: Network topology of BEENISH

5.3 Proposed BEENISH and iBEENISH protocols

This section presents the brief over view of our proposed scheme BEENISH, then we describe iBEENISH. Selection criterion of CHs in BEENISH considers the residual energy of nodes and the average energy level of the network. Moreover, BEENISH considers a heterogenous network with four different energy level nodes (i.e., normal, advanced, super and ultra super).

Rotating epoch is defined with n_i that represents number of rounds for a node s_i in which it can become a CH, where $i = 1, 2, ...N$. Energy consumption of CH (node) is greater than member nodes in a cluster. If p_{opt} represents the optimal probability for the selection of CHs in a homogeneous network, then $p_{opt}N$ is the number of CHs per round are ensured on average. n_i is defined as $n_i = \frac{1}{p_{opt}}$, in which each node s_i atleast once becomes CH. We are considering different energy levels among nodes, so when network operation starts, it follows LEACH criteria and epoch n_i is kept constant for all nodes. Due to which there is non-uniform energy distribution. Low energy node can be selected as CH and drains its energy. As a result, less energy nodes die before the nodes with greater energy. To overcome this deficiency, BEENISH rotates the epoch on the basis of nodes' residual energy levels; $E_i(r)$. As a result, energy consumption is balanced because initially nodes with high energy have high residual energy and they are frequently selected as CHs as compared to normal ones. More specifically, ultra super nodes have high frequency to become CH as compared to rest of the three levels. After that super nodes are more frequently selected as CH as compared to remaining two levels. Similarly, normal nodes have less frequency of becoming CH as compared to the advanced nodes. In this way, the load distribution on each node is almost uniform.

Let for epoch n_i, $p_i = \frac{1}{n_i}$ defines the probability of a node to become a CH. Our proposed scheme chooses the average probability p_i to be p_{opt} which ensures that there are p_{opt} number of CHs in each round. Hence, all nodes die at approximately the same time. If the energy levels of nodes are different, then $p_i > p_{opt}$ for high energy nodes.

$\bar{E}(r)$ represents the average energy of the network during the r^{th} round [79]. It is calculated as follows:

$$\bar{E}(r) = \frac{1}{N} E_{total} (1 - \frac{r}{R}) \tag{5.11}$$

Where, R shows the total number of rounds from start of the network till all the nodes die which is given as:

$$R = \frac{E_{total}}{E_{round}} \tag{5.12}$$

where, E_{round} is the network's energy consumption per round and is calculated as:

$$E_{round} = L(2NE_{elec} + NE_{DA} + k\varepsilon_{mp}d^4_{toBS} + N\varepsilon_{fs}d^2_{toCH}) \tag{5.13}$$

where, number of clusters in every round are denoted by k, CH pays cost in the form of data aggregation energy E_{DA}, distance between CH and BS is represented by d_{toBS}, whereas, distance between node in a cluster and CH is d_{toCH}. If N nodes are randomly deployed in an M^2 region, then

$$d_{toCH} = \frac{M}{\sqrt{2\pi k}}, d_{toBS} = 0.765\frac{M}{2} \tag{5.14}$$

The value of k_{opt} (that is optimal number of clusters in the network) is given below. It is calculated by taking the derivative of E_{round} with respect to k and setting it equal to zero.

$$k_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{M}{d^2_{toBS}} \tag{5.15}$$

The value of threshold probability is calculated in the same manner as authors did in [13, 79]. Based on this value, a node s_i decides whether to become a CH or not. The threshold probability is given below:

$$T(s_i) = \begin{cases} \frac{p_i}{1-p_i(r mod \frac{1}{P_i})} & \text{if } s_i \epsilon G \\ 0 & \text{otherwise} \end{cases} \tag{5.16}$$

where G is the set of nodes which are eligible to be selected as CHs. Set G represents the nodes that do not become CH. These nodes choose a random number between 0 and 1. Then they compare chosen number to the threshold $T(s_i)$, if number is less than threshold value then node s_i becomes CH for that particular round.

As we describe earlier that after certain rounds, the homogenous network becomes heterogenous with multiple levels of energy. In BEENISH, initially we introduce four level heterogeneous network and four types of nodes with different initial energies (normal, advanced, super and ultra super nodes). CH selection probability of normal, advanced, super and ultra super is given below:

$$p_i^{BEENISH} = \begin{cases} \frac{p_{opt}E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Normal\ nodes \\ \frac{p_{opt}(1+a)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Advanced\ nodes \\ \frac{p_{opt}(1+b)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Super\ nodes \\ \frac{p_{opt}(1+u)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Ultra\ super\ nodes \end{cases} \tag{5.17}$$

Above expression shows that nodes with high residual energy has high probability of becoming CH. This strategy is energy efficient and distribute the load among the nodes in a balanced manner. As a result stability period of the network increases. As it is possible that at some stages during the network lifetime three types of greater energy nodes (ultra super, super and advanced) have the same energy as that of normal nodes. In this case, ultra super nodes have high frequency to be selected as CH and they are penalized more than super and advanced nodes. Similarly in comparison to advanced nodes super nodes are more penalized. To avoid this conventional approach for selecting CH, in proposed scheme, probability of node to become CH varies with the varying residual energy. Implementing above mentioned strategy of frequently penalizing the nodes with higher residual energies balances energy consumption resulting in smooth behavior of the proposed schemes.

In this regard, our proposed iBEENISH protocol makes some changes in the probabilities defined in the BEENISH protocol. The difference is based on the absolute residual energy $T_{absolute}$, which varies the probability according to variation in the residual energy. If ultra super, super and advanced nodes drain their energies and their residual energy become equal to same energy level as that of normal nodes. Then the probability of becoming a CH varies and all four kind of nodes will have same probability. The selection probabilities of nodes to become CHs in iBEENISH are given in equation 5.18:

$$p_i^{iBEENISH} = \begin{cases} \frac{p_{opt}E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Nrm\ nodes\ if\ E_i(r) > T_{absolute} \\ \frac{p_{opt}(1+a)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Adv\ nodes\ if\ E_i(r) > T_{absolute} \\ \frac{p_{opt}(1+b)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Sup\ nodes\ if\ E_i(r) > T_{absolute} \\ \frac{p_{opt}(1+u)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Ult\ nodes\ if\ E_i(r) > T_{absolute} \\ \frac{c\times p_{opt}(1+u)E_i(r)}{(1+m(a+m_0(-a+b+m_1(-b+u))))\bar{E}(r)} & for\ Nrm,\ Adv,\ Sup\ Ult\ nodes\ if \\ & E_i(r) \leq T_{absolute} \end{cases} \tag{5.18}$$

Absolute residual energy level is denoted by $T_{absolute}$ and its value is given in equation 5.19:

$$T_{absolute} = zE_0 \tag{5.19}$$

where the value of z lies in the range of $[0, 1]$. If $z = 0$ and $T_{absolute} = 0$, then the scheme working behind is BEENISH. We run the simulation many times varying the value of z. For value of $z = 0.71$ is showing best results in terms of network lifetime. The main objective is to obtain longer stability period. It is observed that it is not necessary that all nodes with higher energy level become CH. There is always an optimal number of CHs in the network. Some times, it is also probable that normal nodes become CH. In figure 5.2 we obtain best results for first dead node using the parameters given in table 5.1.

$$T_{absolute} = 0.71 \times E_0 \tag{5.20}$$

TABLE 5.1: Simulation Parameters

Parameter	**Value**
Network field	100m × 100m
Number of nodes	100
E_0	0.5J
Message size	4000 bits
E_{elec}	50nJ/bit
E_{fs}	10nJ/bit/m2
E_{amp}	0.0013pJ/bit/m4
E_{DA}	5nJ/bit/signal
d_0(threshold distance)	70m
p_{opt}	0.1

Through value c number of CHs are optimized and it is a positive integer. For both smaller and larger values of c, our scheme works in "direct communication" manner. The nodes that are far from the BS consume more energy in long distance transmissions. In order to avoid long distance communication we find the optimum value of c which provides the best results in terms of the death of the first node. For this purpose we run simulations many times by varying value of c between range $[0, 1]$ and find that at $c = 0.02$ network shows better results in terms of the death of the first node at. Figure 5.2 shows how c affects the round in which first node dies.

5.4 Sink mobility

The energy efficiency is the main objective in any WSN so that the network lifetime and stability period can be maximized. Now a days, sink mobility is an effective

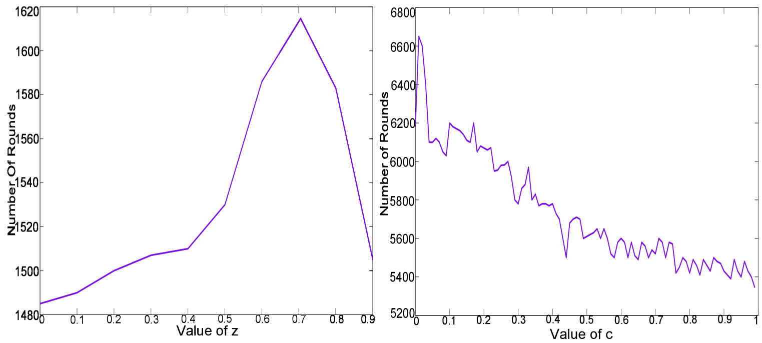


Figure 5.2: Variation round of c and z until the first node dies

way to maximize the network lifetime and stability period of the network. So we introduce sink mobility in BEENISH and iBEENISH protocols and then examine their effects. We put a greater emphasis on the network stability period because a greater stability period gives better and reliable data.

Sink mobility is divided into two classes: un-controlled and controlled mobility [28]. In the first technique, the sink is able to move freely/randomly in the network, whereas, in the second technique the sink can follow only pre-defined path throughout the network lifetime. Furthermore, controlled mobility is of two types. The first one is non-adaptive and non-flexible, which chooses fixed sojourn locations of the sink for the whole network lifetime, whereas the second technique is adaptive, robust and flexible because it chooses sojourn locations for MS in every round in order to maximize the network lifetime. We implement this adaptive technique.

When the sink is static, the probability of getting coverage holes in the network increases. After some time, when network is operational, the energy of few nodes in the network possibly becomes low which can lead toward coverage hole problem. Coverage holes are avoided in WSN because those regions where node die are left unattended and then it became difficult to be monitored. Sink mobility effectively minimizes the generation of coverage holes and balances the energy consumption among the sensors. This is why we implement sink mobility in BEENISH and

TABLE 5.2: Difference between BEENISH, iBEENISH, MBEENISH and iMBEENISH

Scheme name	CH selection probability	Sink type
BEENISH	Depends upon initial energy of a node	Static sink
iBEENISH	Depends upon residual energy of a node	Static sink
MBEENISH	Depends upon initial energy of a node	Mobile sink
iMBEENISH	Depends upon residual energy of a node	Mobile sink + CH

iBEENISH and improve the stability period of both of them. Sink mobility versions of BEENISH and iBEENISH are MBEENISH and iMBEENISH, respectively.

5.4.1 System model

In our system model, network follows the following assumptions:

1. The considered WSN is proactive. All nodes in the network generate equal amount of data per unit time.
2. Each data unit is of the same length.
3. All nodes have the same transmission range.
4. Each node has a unique pre-defined id.
5. Protocol operation has rounds that are equal time slots.
6. At the beginning of each round, new sink locations are computed which remain fixed during that round.
7. Sinks have no energy constraint and able to move from one sink location to another.
8. Sink moves to a location outside the network for recharging fuel or electricity.

5.4.2 Issues to be tackled in sink mobility

A MS is usually driven by fuel and/or electricity, that is why, the total travel distance covered by the sink throughout the network lifetime should be bounded. When a MS moves from one sink location to another, the probability of data loss is high, so, the distance between two sink locations should be at minimum. Adaptive sink mobility requires that the sink must re-construct the routing table or routing tree at each new location, which takes a specific time. So, a MS should reside for a minimum amount of time at each sink location. The transmission of data from nodes/CHs to a sink only occurs when the sink is not moving, i.e., sink is located at any sink location. Therefore, the sum of stop times in a MS tour should be maximized. There should be maximum number of stop locations for a MS so that the throughput is maximized.

Another important issue that we elaborate on here is the use of sink mobility in a clustered environment. Most of the recent research works implement sink mobility in cluster-less topologies. The reason behind this is non-compatibility between clustering and sink mobility. If we apply the same sink mobility in a clustered environment and a cluster-less environment taking all other parameters constant, the comparison shows that the network lifetime and stability period of cluster-less protocol is much better than the clustered protocol. We tackle this issue efficiently and implement the sink mobility in our clustered heterogeneous protocol MBEENISH and iMBEENISH that results in prolonged network lifetime and extended stability period [80].

5.4.3 MS model

In this subsection, we propose a mathematical model of sink mobility *MS Model* (MSM) in which we take a single sink that can move to certain sink locations in every round. Sink locations are determined at the start of every round in our proposed model, in order to increase the network lifetime. Therefore, this model is an adaptive sink mobility model.

Our proposed protocols; MBEENISH and iMBENISH, select CHs on the basis of probability and high energy nodes have greater probability to become CHs.

So, the sink mobility mechanism in MSM includes selection of sink locations in every round which are most feasible towards the network lifetime maximization. In the start of every round, the energies of all CHs are compared and the CHs with minimum energies, are selected. After that, the locations of these minimum energy CHs are chosen to be the sink locations for that particular round. In our proposed protocols, the sink is actually making transmission easy for those CHs which are left with less energy than other existing CHs. When the sink is at a sink location $k \in \gamma_0$, it harvests data from that minimum energy CH. If a node has a sink location in its communication range then it sends the data to the sink when it reaches that location, otherwise it sends the data to its nearest CH. Node waits for the sink on most closer sink stop, in case of more than one sink locations in its communication range. The same happens with the CHs in every round, each CH checks for the sink locations and finds the closest location to it and then sends its aggregated data when the sink reaches that closest location.

The WSN is modeled through directed graph $\{G = \gamma \cup \gamma_0,\ \pounds \cup \pounds_0\}$, where $\mid \gamma \mid =$ N and γ_0 is the set of sink locations. Set of nodes is represented by N. $\pounds = \{\ \gamma \cup \gamma\ \}$, is the set of edges/links between nodes and $\pounds_0$ is the set of edges/links between sensor nodes and sink locations. Set of wireless links between sink locations and nodes are given by $\pounds_0 = \{\ \gamma \cup \gamma_0\ \}$. σ_i is the data generation rate and it is same for all sensor nodes. ℓ_{ij} is the wireless link between i and j sensor nodes and ℓ_{ij} $= 1$, if i and j are within each other's communication range τ_i otherwise $\ell_{ij} = 0$, where $\forall i, j \in N$. The wireless link between a sensor node and a CH is shown by ℓ_{ic}, where c can be any CH. The link between a sensor node and a sink location is given by ℓ_{ik}.

We consider the bounded distance for MS because it is either driven by petrol or by electricity. It gets recharged or refueled after covering certain distance. Moreover, starting and ending point of the MS is considered same and that location is denoted by 'ρ'. In this case, this location is outside the network because MS gets recharged/refueled there. The stop time of the sink at each sink location is given as χ_k^r. This is the time in which the MS gathers data from nodes/CH when it is at the sink location $k \in \gamma_0$, during round r. The speed of the MS is assumed to be infinity as the speed between two stops is consider negligible as compared to its stay on sink location. δ_{ij} is the data amount from node i to node j, δ_{ic} represents the amount of data from node i to CH ȷ and δ_{ik} shows the data amount from node i to sink location k. The energy dissipated in transmission of unit data from node i to node j is given as e_{ij}^t. Whereas, e_{ic}^t is the energy consumed for transmitting one unit of data from node i to CH c. And e_{ik}^t is the energy consumed for transmitting one unit of data from node i to a sink location k. The initial energy for normal nodes is given by:

$$E_i = E_0 \tag{5.21}$$

Initial energy of advanced nodes is shown by:

$$E_i = E_0(1 + a) \tag{5.22}$$

Super nodes have initial energy given by:

$$E_i = E_0(1 + b) \tag{5.23}$$

Ultra super nodes have initial energy:

$$E_i = E_0(1 + u) \tag{5.24}$$

$$Maximize\left(X = \sum_r \sum_k \chi_k^r\right) \tag{5.25a}$$

$$\text{subject to: } \lambda_{ck} \in 0, 1, \quad \forall c, k \tag{5.25b}$$

$$\sum_{k} \lambda_{ck} = \begin{cases} 1 & \text{if } \delta_{ic} = 0, \\ 0 & \text{Otherwise} \end{cases} \tag{5.25c}$$

$$\sum_{r} \left(e^T_{ij} \sum_{\ell_{ij}} \delta^r_{ij} + e^T_{ic} \sum_{\ell_{ic}; i \neq c} \delta^r_{ic} + e^T_{ik} \sum_{\ell_{ik}} \delta^r_{ik} + e^R \sum_{\ell_{ji}} \delta^r_{ji} \right) \leq E_i, \forall i \tag{5.25d}$$

$$\sum_{c} \Lambda^r_{c\rho} = 1, \quad \textit{for any } r \tag{5.25e}$$

$$\sum_{c} \Lambda^r_{\rho c} = 1, \quad \textit{for any } r \tag{5.25f}$$

$$\chi_k > 0, \delta_{ij} \geq 0, \forall k, i, j \tag{5.25g}$$

$$\forall i, j \in \gamma, \forall c \in \gamma, \forall k \in \gamma_0 \tag{5.25h}$$

This model is a mixed integer linear programming model. We explain each equation below:

- **Initial energy**: As MBEENISH and iMBEENISH protocols are heterogeneous, therefore these protocols utilize four levels of energy. So, the initial energy of normal nodes is given by equation 5.21 which is E_0. Similarly, the initial energy of advanced nodes is given by equation 5.22. Equation 5.23 represents the energy of super nodes at the start of the network. Equation 5.24 depicts the initial energy of ultra super nodes which is 'u' times greater than the initial energy of normal nodes.
- **Objective function**: The objective of MSM is to maximize the network lifetime which is shown by equation 5.25a. This objective is achieved by maximizing the sum of all stop times of the sink throughout the network lifetime. The reason behind this is simple, i.e., the sink collects data from nodes or CHs whenever it is not moving (the sink is at any sink location k).
- **Flow constraints**: In constraint 5.25c, λ_{ck} is an indicator function which

shows that sink location k is co-located with the location of a CH c. λ_{ck} is 1 only when the amount of data from node i to CH c is 0 which is written in 5.25b as $\delta_{ic} = 0$. Equation 5.25b shows that the amount of data received by a CH c is zero when sink location k is co-located with that CH. Because all the nodes present in that cluster send their data to k whenever the sink arrives there.

- **Energy constraint** 5.25d: This constraint shows that the total energy spent by node i throughout the network lifetime should be less than its initial energy. Node i spends its energy while transmitting data to other nodes, to a CH or to a sink at its respective location. In addition, the node i consumes its energy in receiving data from other nodes whenever it acts as a CH. This constraint is valid for all nodes i $\in \gamma$. In our protocol, nodes do not use multi-hop transmissions, therefore, a node only sends data to a CH or to the MS. So, δ^r_{ij} and δ^r_{ji} will be zero in our proposed schemes.
- **Sink movement**: Constraints 5.25e and 5.25f elaborate that the sink starts from ρ and goes through different sink locations in the network and then returns back to ρ for recharging. $\Lambda_{c\rho}$ is an indicator function which shows that the sink goes to an external location after every round. $\Lambda_{c\rho} \in \{0,1\}$, where $\Lambda_{c\rho}$=1 only when the sink moves from the CH 'c' to ρ.
- **Constraint**: Constraint 5.25g shows that the stop times of the sink should be greater than zero because the sink has to collect data when it is stopped. And constraint 5.25h depicts the corresponding sets of different variables.

5.4.4 Packet retransmissions model

Wireless communication faces many impairments like interference, attenuation, noise, etc. Radio waves in free space travel over a single well-defined radio path, however, in the air medium they get scattered. This scattering occurs due to the reflection from obstacles present near mobile antennas. Reflection of waves causes attenuation or packet drop. As a result user receives rapidly varying signal. Therefore, in real scenarios, there is always a probability of packet loss in wireless transmissions. So, whenever a packet is dropped on a link ℓ_{ij}, node i retransmits that packet and waits for the acknowledgement again. So, it means the number of dropped packets is directly proportional to the number of packets' retransmissions. We present a mathematical model with the objective of minimizing the number of retransmissions. The objective function and its constraints are given below:

$$Minimize\left(\Psi = \sum_{r} \digamma^{r}\right) \tag{5.26a}$$

Subject to:

$$d_{ic} \leq d_{max}, \forall i, c \in \gamma \tag{5.26b}$$

$$d_{ik} \leq d_{max}, \forall i \in \gamma; \forall k \in \gamma_0 \tag{5.26c}$$

This mathematical model is intended to minimize the number of packets retransmitted in the network. Each equation of this linear programming model is explained below:

- **Objective function**: The objective function in equation 5.26a aims to minimize the total number of packet retransmissions throughout the network lifetime; Ψ. This objective is achieved by minimizing the number of retransmissions in every round. $\digamma^{r}$ is the number of retransmissions in a particular round r. As a result of these packets dropped, the number of packets successfully received by the BS will be less than the number of packets transmitted.
- **Distance constraints**: These constraints show the distance bound between a sender and a receiver. The reason behind this distance bound is that wireless communication at a long distance has the greater probability of packet loss than the short distance wireless communication. So, to minimize

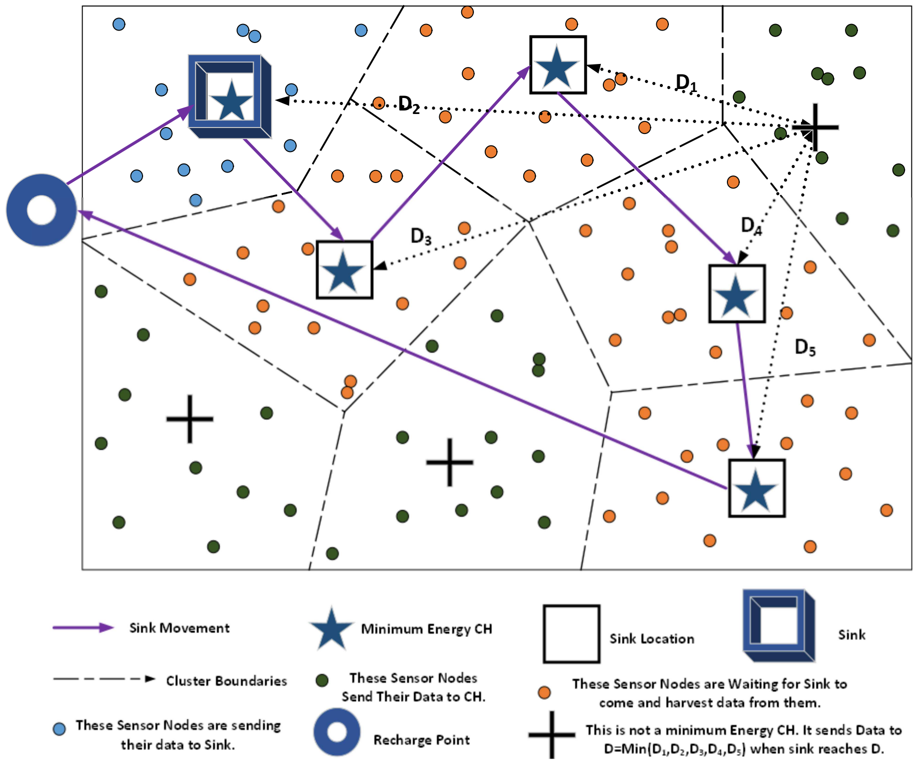


FIGURE 5.3: Sink mobility mechanism

the number of retransmissions, we define the maximum distance between a sender and a receiver to be d_{max}. In constraint 5.26b, d_{ic} shows the distance between a node 'i' and a CH 'c' should be less than this maximum distance. And constraint 5.26c shows that the distance between a node 'i' and the sink location 'k' of MS should be less than or equal to d_{max}, otherwise, the probability of packet drop is greater.

5.4.5 Mechanism of sink mobility in MBEENISH and iMBEENISH

This subsection clarifies the mechanism of sink mobility which is used in our proposed scheme. Figure 5.3 shows the sink mobility mechanism of MBEENISH and iMBEENISH in a round. In every round, the MS has to start its journey from ρ, and step by step sojourn at minimum energy CHs in the network and then the

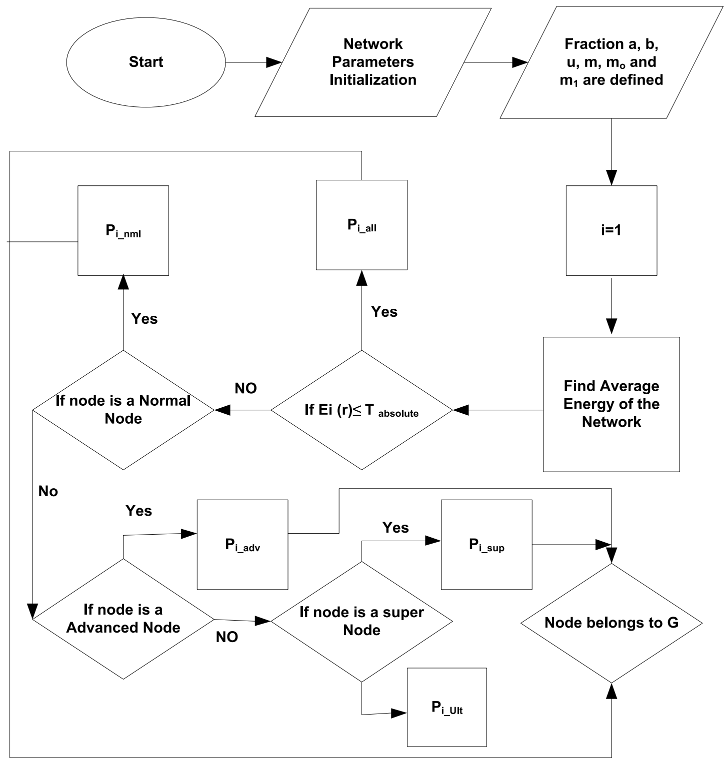


FIGURE 5.4: Module 1: Finding normal, advanced, super and ultra super nodes

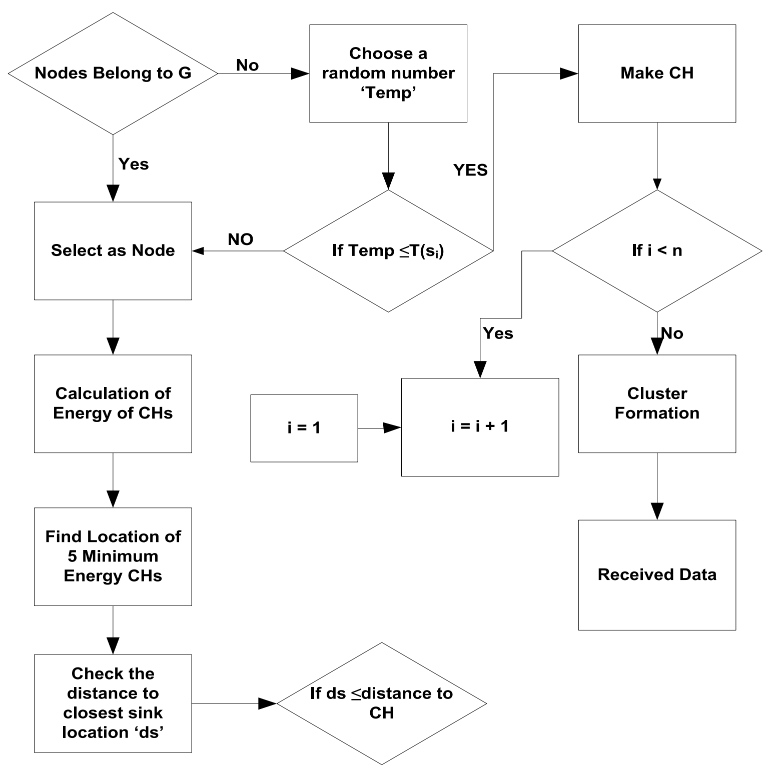


FIGURE 5.5: Module 2: Cluster formation and selection of CHs

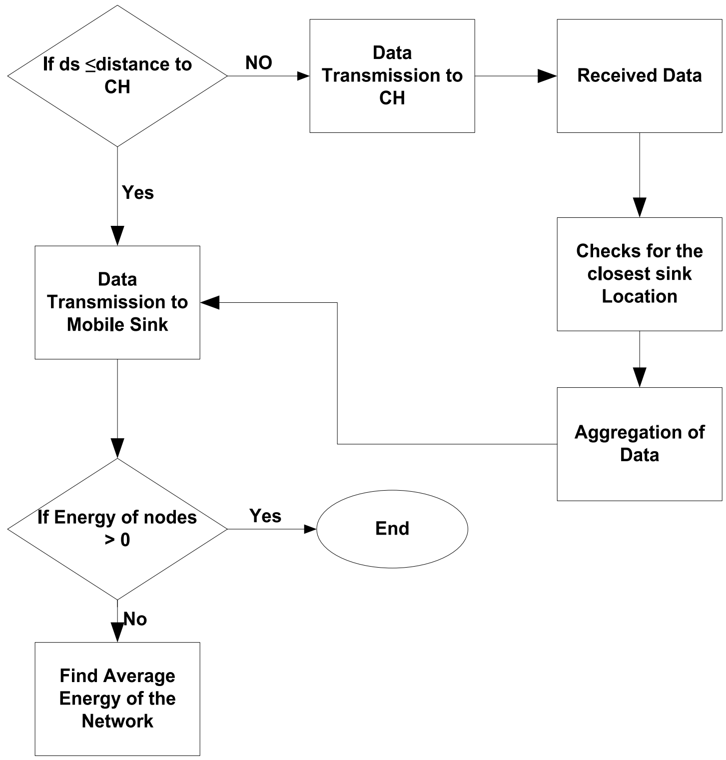


FIGURE 5.6: Module 3: Transmission on the basis of minimum distance

MS has to return back to ρ. This movement of the sink from ρ to a CH inside the network area and from CH to ρ is depicted in equation 5.25e and equation 5.25f of the MSM, respectively. This is the tour of MS in a single round. The MS checks for the minimum distant sink location to its current location and then goes to that sink location which is at a shortest distance. MS is staying on the minimum energy CH for gathering data and minimizes its load. Being part of the same network, if a CH dies, the system can become unstable. Nodes in blue color represents the cluster where the energy of CH in minimum, they send their data to the MS directly instead of sending it to their CH to save their energy as depicted in equation 5.25b of the MSM. Orange colored nodes are sensing the parameters but they are not sending the data to anyone because the sink has to pass through their cluster. So, these nodes keep queuing the data in their buffers until the MS reaches their cluster. In figure 5.3, nodes in the green color sense the parameters but they do not send the data directly to the MS for energy efficiency. The CH after receiving data from these nodes, aggregates and sends to the shortest distant sink location.

To elaborate the working of iMBEENISH, we present the whole scheme into three modules. First module in figure 5.4, finds normal, advanced, super and ultra super nodes. In second module, shown in figure 5.5 clusters are formed. The CHs' selection technique in our protocol is totally based upon probabilities which are assigned to each node on the basis of their residual energies. After clustering, the association of nodes with CHs takes place and clusters are formed. In third module, figure 5.6, represents the data transmission from nodes and CHs, where every node checks whether to transmit its data to its corresponding CH or directly to the MS. After that, CHs aggregate and send the data to the MS, when the MS comes to the most feasible closest location. In this procedure, sink mobility enables the nodes and CHs to transmit their data with minimum energy consumption.

5.5 Simulation results

In this section, we assess the performance of BEENISH, iBEENISH, MBEENISH and iMBEENISH protocols.

5.5.1 Performance metrics - definitions

The performance parameters used for evaluation of these protocols are stability period, network lifetime and packets sent to the BS, and packets received at the BS (definitions given in chapter 3, section 3.5.1). Whereas *stability period* is the duration from the start of the network till the death of the first node, whereas, the instability period is the period from the death of the first node till the death of the last node.

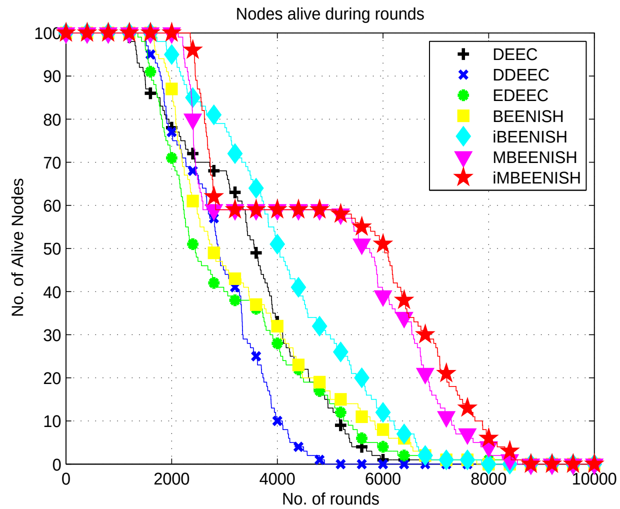
5.5.2 Performance metrics - discussions

We consider a WSN where, 100 nodes are randomly deployed in the $100m \times 100m$ network field. We are not considering energy loss due to signal collisions and interference between signals of different nodes that are due to dynamic random channel conditions. Table 1. represents the radio parameters we used in the proposed schemes simulations. We compare the proposed schemes (variants of BEENISH) with DEEC, DDEEC and EDEEC.

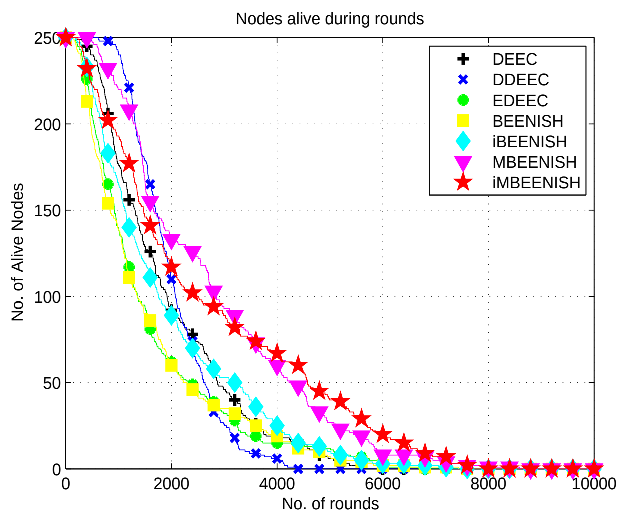
For simulations, we consider network that contains 40 normal nodes having E_0 initial energy, whereas, 30 advanced nodes ($m = 0.6$ fraction of normal nodes) with 2 times more energy ($a = 2.0$) than normal nodes. The 21 super nodes ($m_0 = 0.5$ fraction of normal nodes) containing $b = 2.5$ times more energy than normal nodes. Finally, 9 ultra super nodes ($m_1 = 0.3$ fraction of normal nodes) containing $u = 3$ times more energy than normal nodes. All Nodes remain alive until their energy is consumed. Figure 5.7 shows alive nodes against the number of rounds. First node of DEEC, DDEEC, EDEEC, BEENISH, iBEENISH, MBEENISH and iMBEENISH dies at 1287, 1523, 1595, 1754, 2046, 2237 and 2421 rounds, respectively, and all nodes die at 6520, 5144, 8046, 8109, 8521, 8630 and 9102 rounds, respectively. Figure 5.7 shows that alive nodes in BEENISH and iBEENISH gradually die which means that these two protocols are more efficient protocols than DEEC, EDEEC and DDEEC. Nodes die in the following sequence: normal, advanced, super and ultra super. When a, b, u, m, m_o and m_1 are changed; the resulting network lifetime, stability period and the behavior of the network also change. BEENISH and iBEENISH are performing much better than the other protocols because the threshold we set for the probability of nodes extend the network lifetime and stability period as shown in figure 5.7. From this figure, the stable period of MBEENISH is 92% of the stable period of iMBEENISH. Similarly, the stable period of iBEENISH is 85% of that of iMBEENISH. In the same way, BEENISH is 74% of iMBEENISH in terms of stability period. DEEC, DDEEC and EDEEC are 54%, 63% and 66% of iMBEENISH protocol in terms of stability period. Figure 5.7 (b, c) show that with the variation in the dimensions of network from $100m \times 100m$ to $250m \times 250m$ and $500m \times 500m$, with varying number of nodes from 100 to 250 and 500 respectively, the network becomes sparse and nodes consume more energy during network establishment and transmissions.

Sink mobility prolongs the network lifetime and stability period to a greater extent as shown in figure 5.7. The sink moves from one location to the other and sojourns for a certain time making virtual sojourn regions. The MS collects data from CHs and nodes which are lying in its current virtual sojourn region, then moves to a next location and collects data from nodes and CHs of that sojourn region. The stability period of iMBEENISH is approximately 2350 rounds greater than iBEENISH and the stability period of MBEENISH is almost 2000 rounds more as compared to BEENISH. If we do not apply clustering in the network then these protocols will improve effectively. This is because the sink mobility along with clustering is a difficult task to handle. MBEENISH and iMBEENISH are more energy efficient as compared to DEEC, DDEEC and EDEEC as shown in figure 5.7. This is because, the MS goes to minimum energy sink locations to collect data from CHs and nodes. This results in efficient consumption of energy. It is clearly seen from the results that MBEENISH and iMBEENISH are more efficient than the other selected protocols in terms of stability period, network lifetime and packets sent to the BS even in the case of when the network contains more super and advanced nodes as compared to normal nodes.

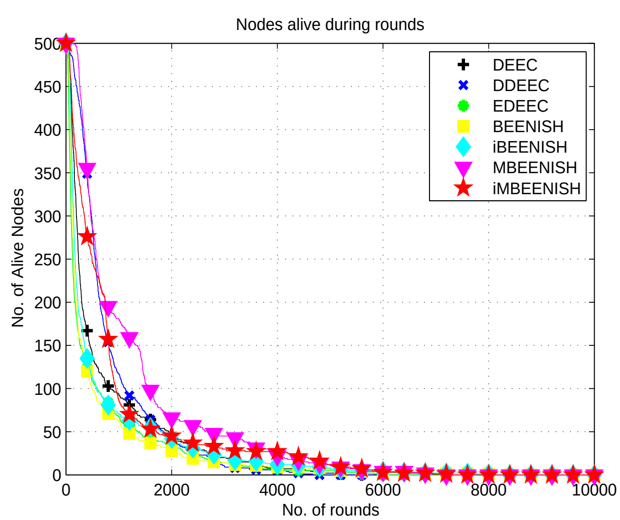
Figure 5.8 shows that MBEENISH and iMBEENISH send more number of packets



(a) Alive nodes for network dimensions $100m \times 100m$ with 100 nodes

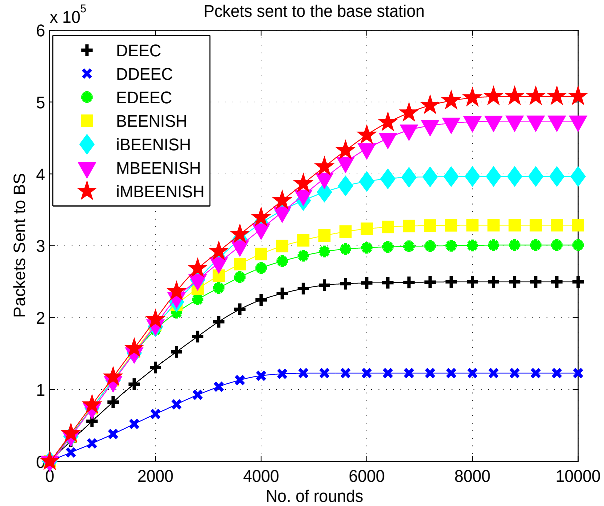


(b) Alive nodes for network dimensions $250m \times 250m$ with 250 nodes

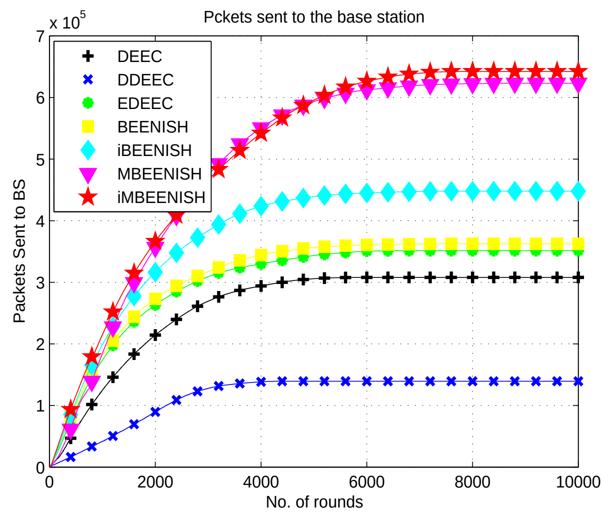


(c) Alive nodes for network dimensions $500m \times 500m$ with 500 nodes

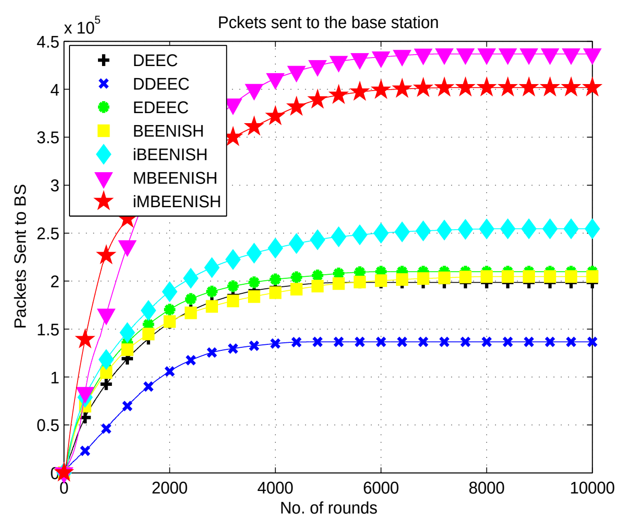
FIGURE 5.7: Alive nodes during network lifetime



(a) Throughput for network dimensions $100m \times 100m$ with 100 nodes

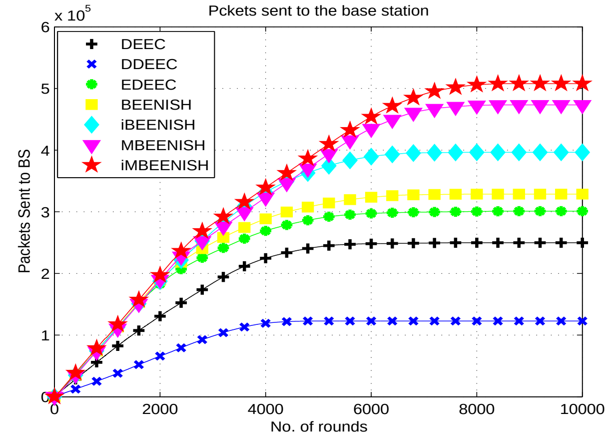


(b) Throughput for network dimensions $250m \times 250m$ with 250 nodes

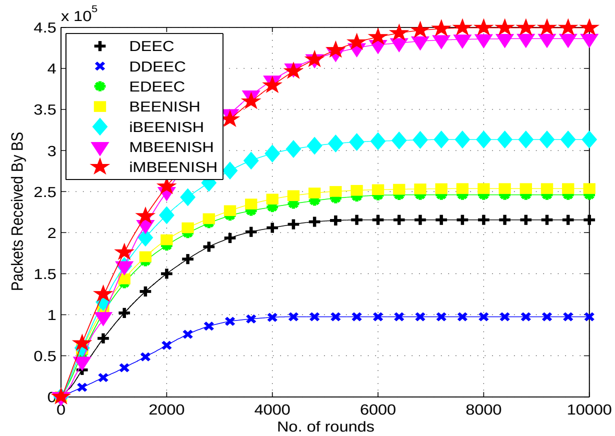


(c) Throughput for network dimensions $500m \times 500m$ with 500 nodes

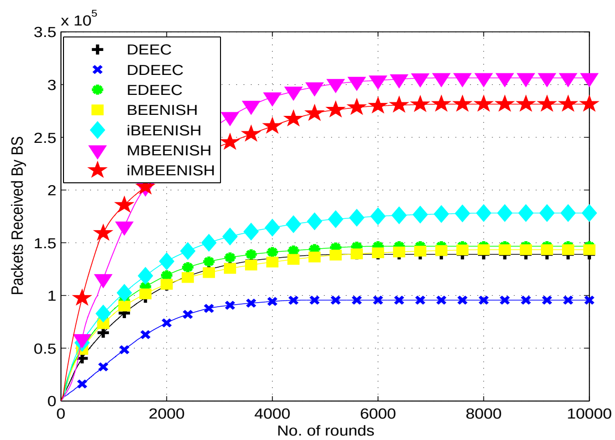
FIGURE 5.8: Throughput of the network



(a) Packets received at BS for network dimensions $100m \times 100m$ with 100 nodes



(b) Packets received at BS for network dimensions $250m \times 250m$ with 250 nodes



(c) Packets received at BS for network dimensions $500m \times 500m$ with 500 nodes

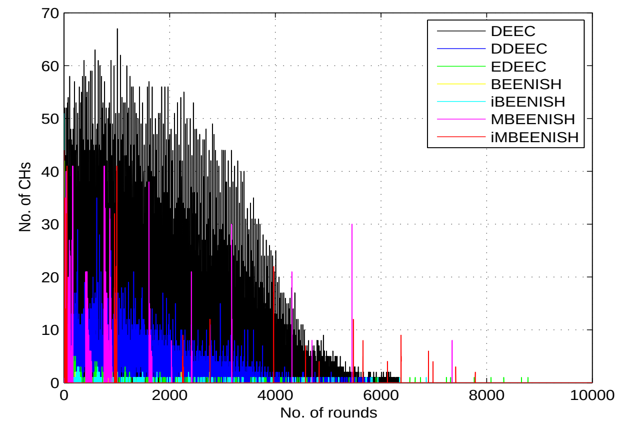
FIGURE 5.9: Packets received at BS

to the BS as compared to the other selected protocols because every node checks the distance between its corresponding CH and the BS, and send packets to the BS if it is at a shorter distance. Packets sent to the BS by nodes and CHs, collectively make BEENISH, iBEENISH, MBEENISH and iMBEENISH better than DEEC, DDEEC and EDEEC. This is because DEEC, EDEEC and DDEEC use clustering in such a way that the BS does not receive that much packets from non-CH nodes. But in iMBEENISH and MBEENISH, the sink goes near to the CHs and collects data. It also collects data from nodes which find it closer than their corresponding CHs. According to MSM, MS sojourns at minimum energy CHs locations in the network and gathers the data from those CHs. Also, the sink collects data from every node which has any sink location in its communication range. Thus, this can lead to an increased number of packets sent to the BS. Throughput of the expanded network fields with extended number of nodes are shown in figures 5.8 (b, c). In 5.8 (b), the throughput of iMBEENISH and MBEENISH is almost the same. Figure 5.8 (c) depicts that in initial rounds, iMBEENISH has higher throughput than MBEENISH, however, after that MBEENISH has higher throughput because with 500 nodes in $500m \times 500m$ network dimensions it has longer stability period. Wireless links have slightly higher probability of bad link status and there are chances that some of the packets may dropped on their way. So, figure 5.8 and figure 5.9 show that packets received are not the same as packets sent in every round using (Random Uniformed Model for dropped packets [83]). When nodes start to die, packets received at the BS also start to decrease, when all nodes are dead throughput curve saturates(not increasing). In DEEC, the selected CHs vary with time. As a result, the number of received packets at the BS also vary. As shown in figure 5.9, the packets received are 30% less than the packets sent to the BS which is shown in figure 5.8. Packet received for the networks with increased area (and more number of nodes as compared to the previous scenarios) are shown in figure 5.9 (b, c). The experimental results show that with increase both in field dimensions and in number of nodes, throughput of the network increases. Also number of packets received by BS increases.

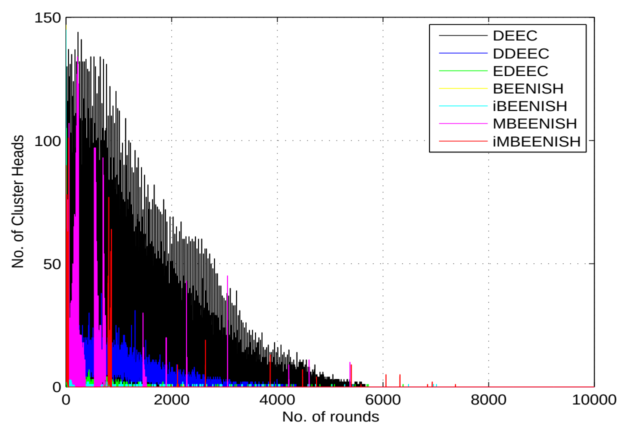
Figure 5.10 shows the rate at which CHs are selected in DEEC, EDEED, DDEEC, BEENISH, iBEENISH, MBEENISH and iMBEENISH. From this figure, we observe that among the selected routing protocols, DEEC has the highest rate of CH selection. Since the CH selection in DEEC, DDEEC and EDEEC is totally based on random number and threshold value and this criteria does not guarantee optimum number of CHs. Due to this reason, surplus CHs are selected which cause an early stage death of nodes in the respective protocols. Our proposed protocols also depend on random number, however we compensate this deficiency by adjusting the probability of CHs' selection. In this way, the chances of CH selection tend towards its optimal value (as per our proposed protocols). Rate of CH selection decreases with new field dimensions and increased number of nodes, as obvious from figure 5.10 (b, c) due to sparsity.

5.5.3 Performance metrics - Trade-offs

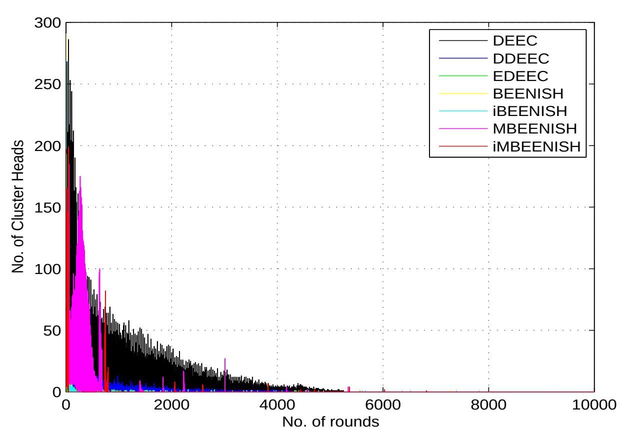
DEEC and DDEEC start from two energy levels whereas, EDEEC starts from three energy levels. BEENISH protocol utilizes four energy levels of nodes. Normal nodes have the least initial energy level and ultra super nodes have the highest initial energy level. In BEENISH, CHs are selected based upon the ratio between residual energy of each node and average energy of the network. Nodes with higher energy are more often selected as CHs as compared to the lower energy ones. Rest more energy three nodes are more punished than the normal ones in BEENISH. iBEENISH solves this problem by dynamically adjusting the CH selection probability. Results show that BEENISH and iBEENISH achieve longer stability periods, enhanced network lifetime and increased number of messages



(a) Rate of CH selection for network dimensions $100m \times 100m$ with 100 nodes



(b) Rate of CH selection for network dimensions $250m \times 250m$ with 250 nodes



(c) Rate of CH selection for network dimensions $500m \times 500m$ with 500 nodes

FIGURE 5.10: Rate of CH selection

sent to the BS as compared to DEEC, DDEEC and EDEEC, respectively. The sink mobility version of the proposed BEENISH and iBEENISH perform better than the non-sink mobility versions in terms of the selected performance evaluation parameters. A comprehensive analysis of performance metrics is presented in table 5.3.

Sink mobility extends the network lifetime and stability period to a greater extent. The sink moves from one location to the other and sojourns for a certain time making virtual sojourn regions. The MS collects data from CHs and nodes which are lying in its current virtual sojourn region, then moves to a next location and collects data from nodes and CHs of that sojourn region. The stability period of iMBEENISH is approximately 2350 rounds greater than iBEENISH and the stability period of MBEENISH is almost 2000 rounds more as compared to BEENISH. If clustering is not applied to the network then these protocols will improve effectively. This is because the sink mobility along with clustering is a difficult task to handle. MBEENISH and iMBEENISH are more energy efficient as compared to DEEC, DDEEC and EDEEC as shown in figure 5.7. This is because, sink mobility is incorporated along with clustering to rescue minimum energy CHs.

Table 5.3: Performance Trade-offs made by the routing protocols

Protocol	Achievement	Reference	Price to Pay	Reference
iMBEENISH	More Alive nodes	Figure 5.7	Rate of CH selection	Figures 5.5, 5.10
	Packets sent to BS	Figure 5.8	Distance computation between CH and BS	Figure 5.6
	Packets received at BS	Figure 5.9	Sink movement to the CHs	Figure 5.3
	Rate of CH selection	Figure 5.10	energy consumption	
MBEENISH	More Alive nodes	Figure 5.7	Sharp energy depletion	
	Packets sent to BS	Figure 5.8	Distance computation between CH and BS	Figure 5.6
	Packets received at BS	Figure 5.9	Sink movement to the CHs	Figure 5.3
	Rate of CH selection	Figure 5.10	lower stability period	Figure 5.1
iBEENISH	More Alive nodes	Figure 5.7	Sharp energy depletion	
	Packets sent to BS	Figure 5.8	Changes CH selection probability dynamically	Figure 5.10
	Packets received at BS	Figure 5.9	CH selection of high-energy nodes	Figure 5.10
	Rate of CH selection	Figure 5.10	Redundant transmission	
BEENISH	More Alive nodes	Figure 5.7	Sharp energy depletion due to 4 types of nodes	Figure 5.1
	Packets sent to BS	Figure 5.8	Rate of CH selection	Figure 5.10
	Packets received at BS	Figure 5.9	Rate of CH selection	Figure 5.10
	Rate of CH selection	Figure 5.10	Sudden energy depletion	
EDEEC	More Alive nodes	Figure 5.7	Energy consumption due to three nodes forwarding	
	Packets sent to BS	Figure 5.8	Throughput decreases due to packets loss in the mid-way	Figure 5.9
	Packets received at BS	Figure 5.9	distant propagations	Figure 5.6
	Rate of CH selection	Figure 5.10	More complexity involved	
DDEEC	More Alive nodes	Figure 5.7	Energy consumption due to two nodes forwarding	
	Packets sent to BS	Figure 5.8	As rounds pass, advanced nodes will have the same CH selection probability like the normal ones	Figure 5.10
	Packets received at BS	Figure 5.9	CH selection	Figure 5.10
	Rate of CH selection	Figure 5.10	Redundant transmission and lower stability period	Figure 5.7
DEEC	More Alive nodes	Figure 5.7	Overhead and complexity of forming clusters	Figure 5.10
	Packets sent to BS	Figure 5.8	Less alive nodes	Figure 5.7
	Packets received at BS	Figure 5.9	Less alive nodes	Figure 5.7
	Rate of CH selection	Figure 5.10	Packets sent and received at BS	Figures 5.8, 5.9

5.6 Chapter conclusion

BEENISH implements the concept of four types of energy levels of nodes, and selects CHs on the bases of residual energy of nodes and average energy of the network. So, in BEENISH protocol, nodes with high energy are frequently selected as CHs as compared to low energy nodes. iBEENISH dynamically changes the CH selection probabilities of high energy nodes when their energy decreases, it increases stability period approx. 12% than BEENISH . BEENISH and iBEENISH show better performance as compared to DEEC, DDEEC and EDEEC, respectively. Whereas, iMBEENISH improved stability period approx. 15% than MBEENISH, 27% than iBEENISH and approx. 37% than BEENISH. Moreover, MBEENISH and iMBEENISH perform better than BEENISH and iBEENISH in terms of the selected performance parameters.

So far we discuss the clustering schemes and we implemented sink mobility there. In next chapter, we implemented sink mobility in the network. MS directly receives the data from nodes and minimizes the energy consumption. Two types of sink trajectories are discussed.

Chapter 6

Defined and random trajectories of MS in homogeneous WSNs with balanced transmission

6.1 Chapter summary

In this chapter, we propose four schemes for data gathering from the network nodes. In the first scheme, sink moves on Random paths in the network (RMS), and we compare it with Defined (DMS) trajectories of MS. To make it clear, we logically divide the field into small squares. Center point of each partitioned area is the sojourn location of the sink whose sensing range is predefined. Nodes directly send sensed data to MS. In the second scheme, we deploy two MSs for data gathering. They follow square trajectories in the network; Geometric Sink Mobility (GSM).

6.2 Proposed schemes: RMS and DMS

The objective of our proposed schemes; RMS and DMS, is to analyze the performance of MS on different trajectories in the field. RMS trajectory follows node density based random path (i.e. density aware motion of MS), whereas, DMS trajectory has a predefined path.

6.2.1 Network model

In our proposed schemes, RMS and DMS, nodes are homogeneous in terms of initial energy. We consider energy consumption only in the transmission of sensed data. A square shaped network area is considered that is further logically divided into sixteen small squares. Nodes are randomly deployed in the network field. The center of each small square is a sojourn location of MS, from where the MS directly receives data from nodes that come in its sensing range (i.e. πr^2) which is shown with dotted lines in figure 6.1. Pause signs are labeled with 1 and 2 to represent two sojourn locations from the whole network field (there are total

16 sojourn locations). These are also labeled as a and c. The intersection area between two circles is shown by shaded region in this figure. The radius of circular sensing range is $r(= r' = r")$ and h is the distance between two intersecting points e and f. When MS moves to the next sojourn location, some portion of previously sensed region also comes in next circular area as shown in figure 6.1. To cope with this problem, nodes that have previously sent their data, do not participate in current transmission. To understand the geometry of transmission ranges (shown in figure 6.1) consider the following approach;

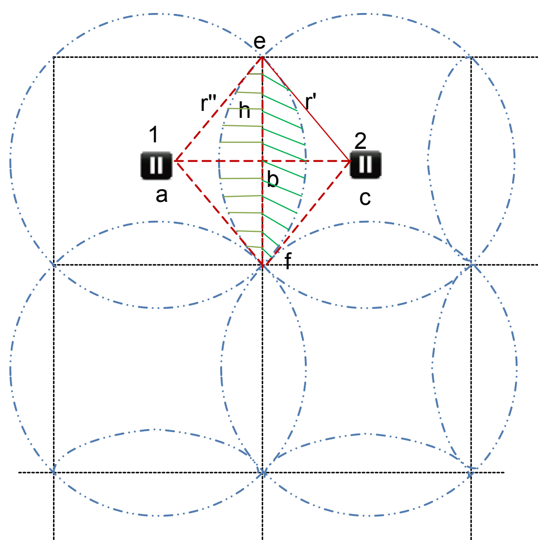


FIGURE 6.1: Overlapping regions in the sensing range

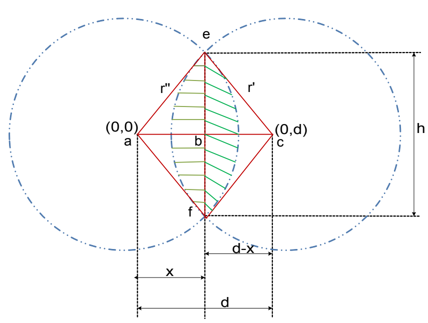


FIGURE 6.2: Cross section of two sensing ranges

When MS stops at a sojourn location, it receives data from the nodes of connected subregions that come in its sensing range. On its forward movement to the next

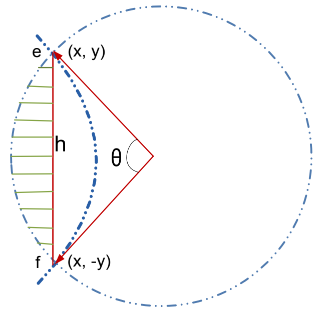


FIGURE 6.3: Co-ordinates and cord of intersected area

location, the MS sensing range overlaps with the previously visited region which may have few common nodes.

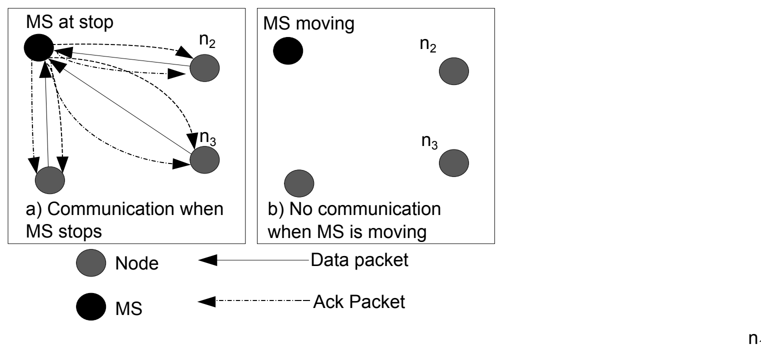


FIGURE 6.4: Incoming and outgoing data flows: a) Nodes are sending data after getting control message, b) No communication when MS is moving

The overlapped sensing range is shown in figure 6.2 to provide more clarity. In order to avoid surplus data reception from nodes that have previously sent their data, a mathematical model is formulated. Both sensing ranges have same radii r, however, to make calculation simple, we label them as r' and r''. Our goal is to calculate the shaded overlapped region between two sensing ranges. For this purpose, we first calculated cord length h with the help of end points e and f, shown in figure 6.3, i.e., (x, y) and $(x, -y)$, where, $h = 2y$. Cord end points are located at the intersection points of circles as shown in figure 6.3. Equation of first sensing range with radius r'' is a circle equation given below:

$$x^2 + y^2 = r''^2. \tag{6.1}$$

Equation for second sensing range with radius r' is:

$$(d-x)^2 + y^2 = r'^2, \tag{6.2}$$

from eq. 6.1 and eq. 6.2,

$$\begin{aligned} x^2 - (x-d)^2 &= r''^2 - r'^2 \\ x &= \frac{d^2 + r''^2 - r'^2}{2d}. \end{aligned} \tag{6.3}$$

Putting value from eq. 6.3 in eq. 6.1,

$$\begin{aligned} y &= [r''^2 - \frac{1}{4d^2}(d^2 + r''^2 - r'^2)^2]^{1/2}, \\ &= \frac{1}{2d}[r''^2 4d^2 - (d^2 + r''^2 - r'^2)^2]^{1/2}, \\ &= \frac{1}{2d}[(2dr'' - (d^2 + r''^2 - r'^2))(2dr'' + (d^2 + r''^2 - r'^2))]^{1/2}, \\ &= \frac{1}{2d}[(r'^2 - (d - r'')^2)((d + r'')^2 - r'^2)]^{1/2}, \end{aligned}$$

$$= \frac{1}{2d}[(r' - d + r'')(r'' + d - r')(d + r'' - r')(d + r'' + r')]^{1/2}. \tag{6.4}$$

In the considered case, radii of both circles are same, i.e. $r' = r'' = r$. Substituting this value in eq. 6.4, we get the value of h.

$$h = 2y = \sqrt{4r^2 - d^2}. \tag{6.5}$$

Area of lens shaped overlapping region is;

$$A = r^2\pi - 2r^2 cos^{-1}[\frac{d}{\sqrt{4r^2 - d^2}}] - \frac{1}{2}d\sqrt{4r^2 - d^2}, \tag{6.6}$$

where 'd' is a distance as shown in figure 6.2. Also, we have considered d as 25 for our proposed schemes RMS and DMS. Eventually, when MS moves onward, already sensed areas are excluded from next location's sensing range given by eq. 6.6. Each node delivers data to MS once during an epoch. To elaborate the proposed schemes, network is modeled as directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ are vertices and $\mathcal{E}$ are edges. In our case we take nodes N as vertices and edges are links between nodes and MS. We define set of sojourn locations as $S = \{s_1, s_2, ..., s_m\}$. For all $i \in \mathcal{V}$ and $j \in S$, $\exists (i,j) \in \mathcal{E}$, iff i and j are within a square transmission range r_{tx}.

MS covers the entire area and directly receives data from each node in epoch (the time duration in which all the nodes send their data to MS once), $n = 0, 1, 2, ...,$. At each sojourn location MS collects data from nodes in its sensing range and then moves on. Traveling time between two sojourn locations is negligible. Link between a node and MS is represented as a_j. Also, if sink sojourn location is s_k, then $a_j = 1$ otherwise $a_j = 0$, $a_j \in 0, 1$.

We maximize network lifetime by using MS on different trajectories.

$$Maximize \quad Z = \sum_n t_n \qquad n = 0, 1, 2, ... \tag{6.7a}$$

$$\text{subject to:} \sum_{s_k \in S} a_j(s_k) = 1 \qquad \forall j \in S \tag{6.7b}$$

$$\sum_i \sum_j f_{ij}^n = \sum_i \sum_j f_{ji}^n \qquad \forall i \in V, j \in S \tag{6.7c}$$

$$\sum_j \sum_i p_{ij} = \begin{cases} Z(\sum_i \sum_j f_{ij}) & \text{if } a_j = 1, \\ 0 & \text{if } a_j = 0 \end{cases} \tag{6.7d}$$

$$\sum_i t_i (\sum_{i \in N} E_{ij}^{tm}) \leq E_{initial} \qquad \forall i \in N, j \in S \tag{6.7e}$$

$$y_{ij} \leq R_{ij} \qquad \forall i, j \tag{6.7f}$$

$$\sum_{i=1}^{n} s_{0,i} = \sum_{i=0}^{n} s_{i,0} \qquad \forall n, S \tag{6.7g}$$

$$y_{ij}, \quad t_i \geq 0 \qquad \forall i, j \tag{6.7h}$$

Eq. 6.7a defines the objective function of maximizing network lifetime. Z is total network lifetime, t_k is the time during one epoch. Therefore, sum of t_n is the total network lifetime. Eq. 6.7b shows that during one epoch sink is located at one stop for the collection of data from nodes that are present in its sensing range. Eq. 6.7c describes incoming and outgoing flow constraints shown in figure 6.4. Function f_{ji} is the amount of data sent over an edge between the node and MS during epoch n and f_{ij} is the hello packet sent by MS during stay on specific sojourn location. Eq. 6.7d refers to collection of data during an entire network lifetime i.e. it can be represented by Z. Eq. 6.7e is the energy conservation constraint. E_{ij}^{tm} is the energy used by the nodes during the transmission of the data towards sink. Whereas, $E_{initial}$ is the initial energy of nodes. Eq. 6.7f is the rate constraint. Total information sent over the link (i, j) should not exceed the link capacity, R_{ij}, it is the upper bound of the transmission rate. Finally, eq. 6.7g shows that starting and ending location of MS is same.

6.2.2 Protocol operation

Another important parameter is sojourn period of MS. Sojourn period is the time duration for which the MS stays at a sojourn location and collects data from the neighboring nodes. In our schemes, sojourn period is adaptively calculated. MS moves to the next location when all nodes of the specific sub-region completely transmit data. We calculate the sojourn period at one sojourn location as;

$t_{n_1} = \frac{t_n}{M}$, where, t_{n_1} is single sojourn time, t_n is total time of a round and M is total number of sojourn locations in the field. If we calculate sojourn time of a complete trip of MS, it shows that time consumed in gathering data during one round is;

$$t_k = \sum_j t_j. \tag{6.8}$$

Therefore, $Z = \sum t_k$ is the total lifetime of the network.

For RMS, MS has global knowledge of all stops on the basis of node density. DMS trajectories are initially defined and MS follows the fixed path.

6.2.2.1 RMS trajectories

RMS trajectory is random because MS collects data on the basis of node density as it moves from dense to sparse region(s). This movement is also very useful as in some cases it is difficult to follow the defined path due to obstacles or hills.

Network field is $100m \times 100m$ which is logically divided into 16 equal sub-regions and the central point of each sub-region is the stop for MS. Sojourn stops M are equal to the number of partitions of field which are 16 in proposed schemes. MS randomly collects data from the nodes, by giving priority to highest node density region. This is due to the fact that the chances of over flow or loss of sensed data increases with an increase in the node density. Also, MS directly collects data from nodes, so, energy used in data transmission is minimized. The complete functionality of RMS is shown in figure 6.5.

The working scheme of RMS is shown in figure 6.6. Logically, MS starts its traveling from dense to sparse sub-region in the network field. We also assume that traveling time is negligible as compared to sojourn time ($t_{n_1} = \frac{t_n}{M}$).

6.2.2.2 DMS trajectories

We assume here a square field in which nodes are randomly deployed. Network field is logically divided into small subregions. Network field dimensions are $100m \times 100m$. It consists of sixteen small squares each of area $25m \times 25m$ each as shown in figure 6.7

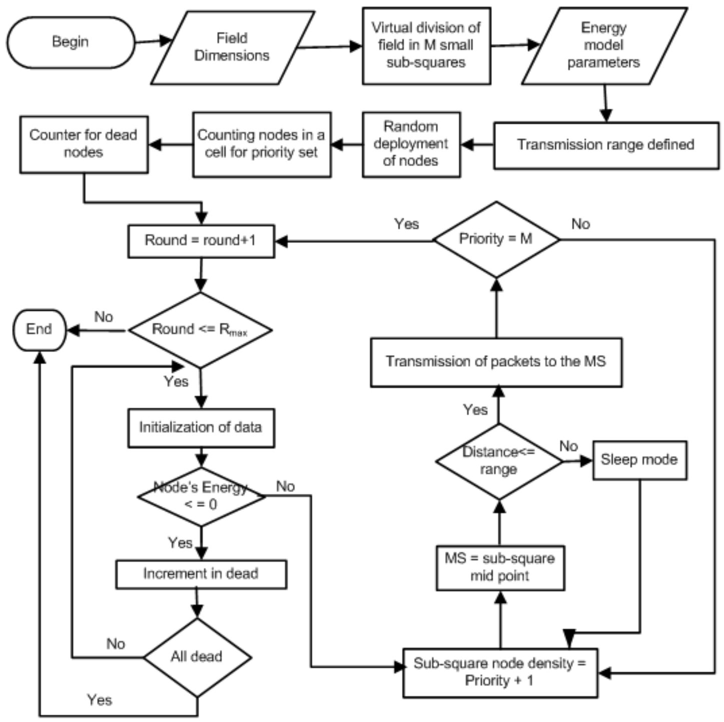


FIGURE 6.5: Flow chart of RMS

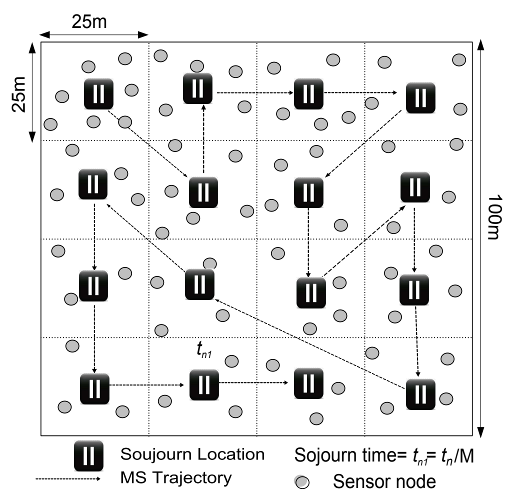


FIGURE 6.6: One of the random paths of RMS

Central point of each sub-region is the sojourn location of MS. Moving pattern of what is predefined as square spiral inside a square field. This trajectory covers the complete area of network. MS stops on a first sojourn location and broadcasts advertisement message to all nodes in its sensing range.

Nodes then establish links and start data transmission. Once data transmission

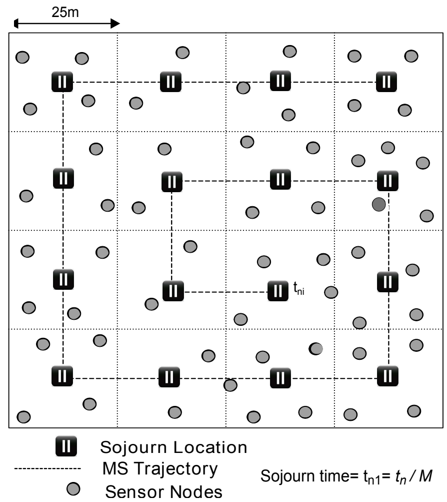


FIGURE 6.7: Path of DMS

is completed, MS moves to the next location and the same procedure is repeated. Working scheme of DMS is pictorially shown in figure 6.8.

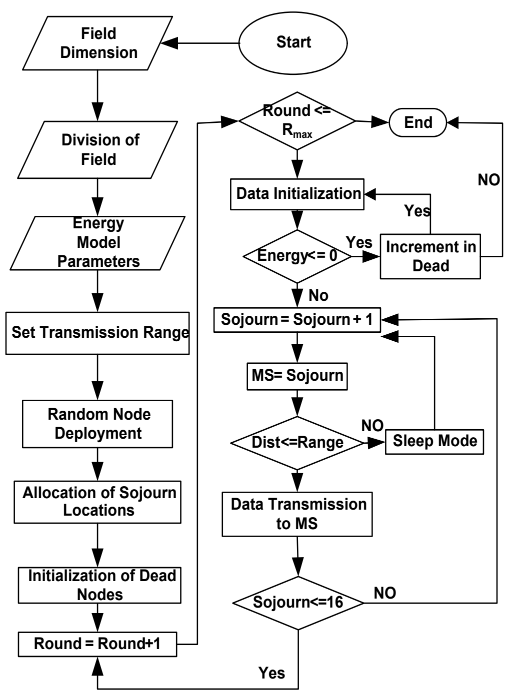


FIGURE 6.8: Flow chart of DMS

All nodes send the sensed data to MS once in a round. MS is aware of its sojourn locations and also has the knowledge of network boundaries. Path of MS is designed in such a way that every node is able to deliver data at a minimum distance.

Moreover, the network is working in a sleep awake manner. Nodes get awake and transmit their data to MS, whenever, they receive a beacon message from MS. Otherwise, nodes go to sleep mode to save their energy. As the area of sub-region is small, minimum energy is used in data transmission.

6.2.3 Analytical analysis

In RMS, regions with high node density, send more packets as compared to DMS. Objective function defines the combined throughput in one complete round trip (i.e., $21 \times 10^3 sec$) .Combined throughput of RMS and DMS is:

$TP - Combined = TP{-}RMS + TP{-}DMS$

Objective function:

$$Maximize \quad TP \tag{6.9a}$$

$$\text{subject to: } 0 \leq (TP\text{–}RMS) + (TP\text{–}DMS) \leq 167Kbps \tag{6.9b}$$

$$0 \leq (TP\text{–}RMS) \leq 100Kbps \tag{6.9c}$$

$$0 \leq (TP\text{–}DMS) \leq 67Kbps \tag{6.9d}$$

According to the bounds provided in eqs. 6.9b, 6.9c and 6.9d; figure 6.9 shows the bounded region formed by intersecting lines $L1, L2, L3$ and $L4$. Combined throughput of both schemes is lying within the boundaries of illustrated region. This bounded region shows the feasible solution. Values on each vertex are obtained as:

at $P1(0,0) = 0Kbps$

at $P2(67,0) = 67Kbps$

at $P3(0,100) = 100Kbps$

at $P4(67,100) = 167Kbps$

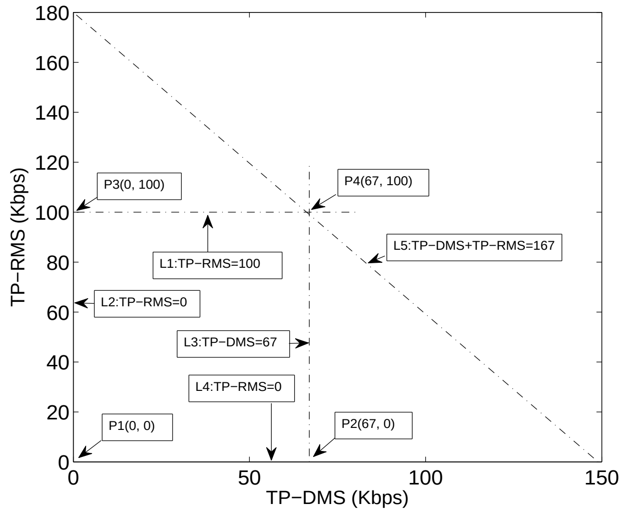


FIGURE 6.9: TP of feasible region

Path loss in RMS is greater than DMS because it receives data from high node density region. As a consequence, diffraction and reflection is greater in this scheme. Feasible region for combined path loss is shown in figure 6.10 in $21 \times 10^3 sec$. Objective function is to minimize PL (Path Loss).

$$Minimize \quad PL \tag{6.10a}$$

where, $PL\text{–}Combined = (PL\text{–}RMS) + (PL\text{–}DMS)$

$$\text{subject to: } 0 \leq (PL\text{–}RMS) + (PL\text{–}DMS) \leq 20654dB \tag{6.10b}$$

$$0 \leq (PL\text{–}RMS) \leq 18578dB \tag{6.10c}$$

$$0 \leq (TP\text{–}DMS) \leq 12076dB \tag{6.10d}$$

Bounded region is formed by the intersection of $L1, L2, L3$ and $L4$ lines. Which shows feasible region of path loss in figure 6.10. These bounds are shown in eqs. 6.9b, 6.9c and 6.9d that forms the feasible region. Values on each vertex are obtained as:

at $P1(0, 0) = 0dB$

at $P2(12076, 0) = 12076dB$

at $P3(0, 18578) = 18578dB$

at $P4(12076, 18578) = 20654dB$

Combined path loss of both schemes is lying within the boundaries of illustrated region.

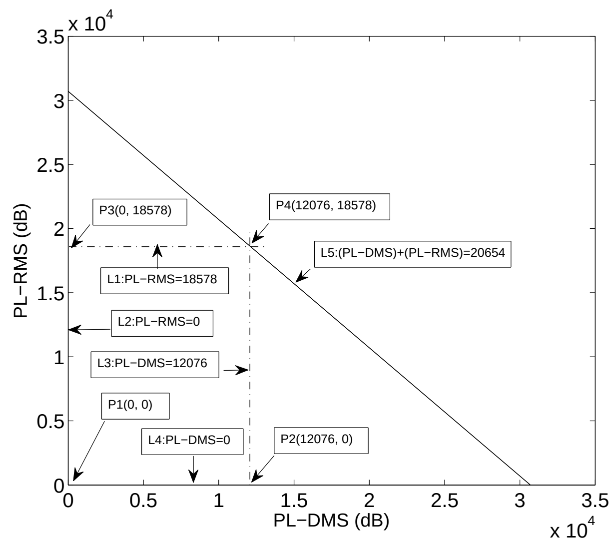


FIGURE 6.10: Path loss of feasible region

Another performance parameter is combined end to end delay of RMS (D-RMS) and DMS (D-DMS) during single trip in which MS gathers data from the field. That is represented as:

$$D - Combined = (D\text{–}DMS) + (D\text{–}RMS) \tag{6.11}$$

Objective function and constraints are given as

$$Minimize \quad D - Combined \tag{6.12a}$$

$$\text{subject to: } 0 \leq (D\text{–}RMS) + (D\text{–}DMS) \leq 0.0102msec \tag{6.12b}$$

$$0 \leq (D\text{–}RMS) \leq 0.0080msec \tag{6.12c}$$

$$0 \leq (D\text{–}DMS) \leq 0.0022msec \tag{6.12d}$$

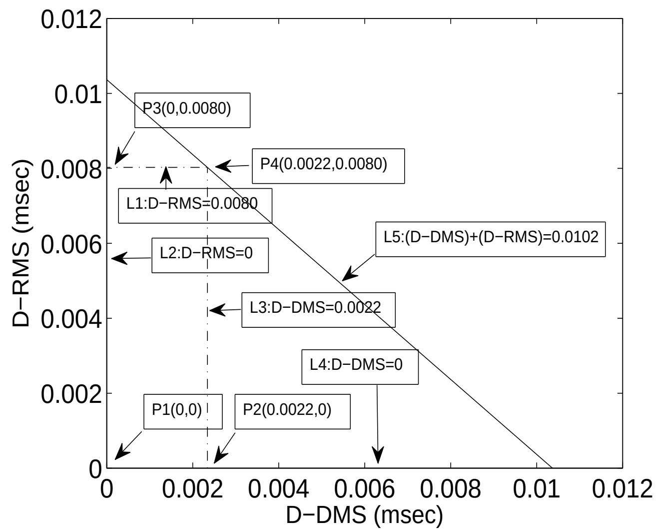


FIGURE 6.11: End to end delay of feasible region

Feasible region is shown in figure 6.11, that is formed by the intersection of $L1, L2, L3$ and $L4$ lines. The values for these bounds are given in eqs. 6.12b, 6.12c and 6.12d. Values on each vertex are obtained as:

at $P1(0,0) = 0msec$

at $P2(0.0022,0) = 0.0022msec$

at $P3(0,0.0080) = 0.0080msec$

at $P4(0.0022,0.0080) = 0.0102msec$

$D - Combined$ falls within the boundaries of illustrated region.

6.2.4 Simulation results

Following performance parameters are considered to evaluate the simulation results.

Table 6.1: Radio parameters

Operation	Energy dissipated
Transmitter / receiver Electronics	$50nJ/bit$
Data aggregation	$50nJ/bit/m^2$
Transmit amplifier (if d to $Sink \leq d_0$)	$10pJ/bit/m^2$
Transmit amplifier (if d to $Sink > d_0$)	$0.0013pJ/bit/m^4$
Data rate	$250kbps$

6.2.4.1 Performance metrics - definitions

For evaluating performance of RMS and DMS, we consider network lifetime, stability period, throughput, packets dropped and end to end delay. Whereas, path loss includes all the propagation losses due to attenuation of electromagnetic waves, refraction, diffraction and reflection, between source and sink. It is calculated in dB. We use first order radio model for energy consumption [13] and distance is taken between source node and MS. For calculating distance we use the equations 1.1, 1.2 given in chapter 1.

Radio model parameters, we used for simulations are shown in table 6.1. 100 nodes are randomly deployed in a network. Network field is logically divided in to 16 small squares of equal area; i.e. $25m \times 25m$. Due to random deployment of the nodes, density of nodes varies in the subregions, where it is high, there are chances of information loss due to data overflow. Our proposed RMS scheme addresses this problem, i.e., MS visits dense region first, whereas, DMS considers predefined paths. In both cases, sojourn locations are defined.

6.2.5 Performance metrics - discussions

Performance parameters are discussed briefly below:

6.2.5.1 Network stability

Figure 6.12 shows the comparison of network lifetime of proposed and compared schemes. DMS shows improved and extended stability period in comparison to the other schemes. MS broadcasts a beacon, when it stops at a particular location. Nodes which come in the transmission range of MS, receive the beacon and transmit their sensed data. As a consequence nodes minimize their energy consumption due to direct and reduced communication distance. This results in longer stability period as well as network lifetime. Sink mobility in the proposed scheme results in reduced energy consumption as compared to the existing schemes. Moreover, the CHs bear the burden of their respective member nodes in terms of data forwarding and aggregation. Thus, the CHs consume energy at faster rate as compared to normal nodes. In DMS and RMS, we compared the mobility patterns; predefined trajectory of MS and random trajectory from dense region to sparse regions of the network, respectively. In RMS, nodes from sparse regions transmit data towards the sink at larger distance, therefore, consuming more energy. As a result, RMS shows shorter stability period, however, its network lifetime is similar to DMS. DREEM-ME has also longer stability period due to uniform random distribution of the nodes and minimum transmission distance. After 4.2×10^7 sec the nodes in the outer most and central region drain their batteries and the nodes present in the inner most region only send data towards the sink. UC-MS has longer network lifetime than LEACH due to the presence of MS.

6.2.5.2 Throughput

Throughput of the proposed and compared schemes is shown in figure 6.13. The schemes with MS have higher throughput because of direct communication between nodes and MS and low path loss. DREEM-ME and FTIEE are clustering routing protocols; their throughput is less than to the other four MS schemes.

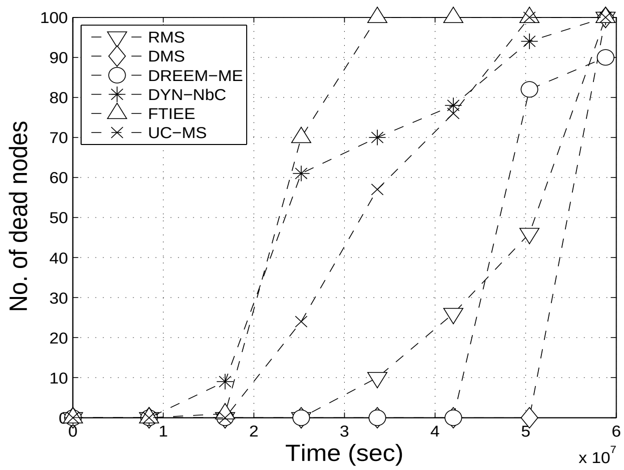


FIGURE 6.12: Stability comparison

RMS has greater throughput because MS gives priority to dense regions for data gathering i.e. more number of nodes directly send data packet, thereby increasing throughput. In UC-MS, CHs collect data from member nodes and wait for the control message from MS (when it arrives on nearby stop). MS visits the pre-determined stops and directly receives data from the CHs at minimum possible distance. This reduces the energy consumption of CHs. DYN-NbC and UC-MS are clustering schemes with sink mobility and are more efficient in comparison with DREEM-ME and FTIEE. However, we further minimize energy consumption by excluding clustering mechanism in RMS and DMS. DYN-NbC contains clustering as well as MS. So its throughput lies in between the throughput of clustering schemes; (FTIEE, DREEM-ME) and, schemes with MS (DMS, RMS). From the start of the network operation, throughput of each scheme linearly increases, whereas, after the end of stability period throughput decreases. Reason for low throughput is decreased number of alive nodes in the network. That shows maximum possible output during one complete trip of MS when it receives data from all nodes.

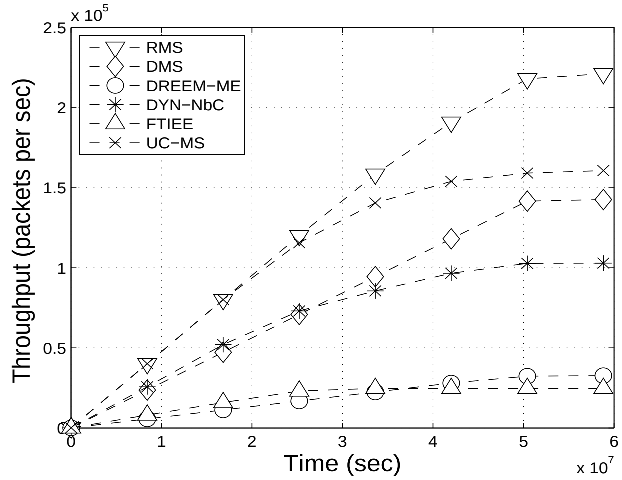


FIGURE 6.13: Number of packets sent to sink

6.2.5.3 End to end delay

End to end delay varies in all schemes. In figure 6.14, DREEM-ME has the least packet delay because it is clustering scheme; number of hops for data transmission decreases and load is well balanced among the CHs and the member nodes. Also, it has uniform random distribution of nodes. DREEM-ME has static clusters and they stay same till the end of network. Its clusters are design in such a way that nodes interact with CHs which further transmit data to sink at a minimum distance. Delay of DMS is the least among the compared schemes that have MS. In this case, MS has defined trajectory and data is received in less time because of assumption that sink's traveling time is negligible between two adjacent sojourn locations. No priority is given to any node in receiving data from nodes when MS is present at any sojourn location. End to end delay of RMS is greater than that of DMS because MS randomly moves in the field to collect data. The analytical analysis of delay of both schemes during a single trip of MS in the network field is shown in figure 6.11. There, bounded region shows the maximum and minimum values of delay. FTIEE is a clustering scheme and it has greater end to end delay as compared to the proposed schemes. This is because nodes first send data to the CH and then CH forward the aggregated data to the sink and takes extra time (i.e. longer delay). It also posses dynamic clustering which rotates clusters after certain time, and again CH selection and association phase occurs. That results in delay. DYN-NbC has higher delay because it utilize clustering as well as MS. Where clustering use multi-hop communication that results in longer delay. First the denser region on the basis of number of nodes, is selected then remaining regions form clusters; and CHs are selected, also, nodes association phase takes place. In UC-MS clustering is done first, then association of nodes occurs. The difference is, CH waits for MS for data forwarding. From the start of the network till the death of first node, end to end delay linearly increasing and afterwards remain constant.

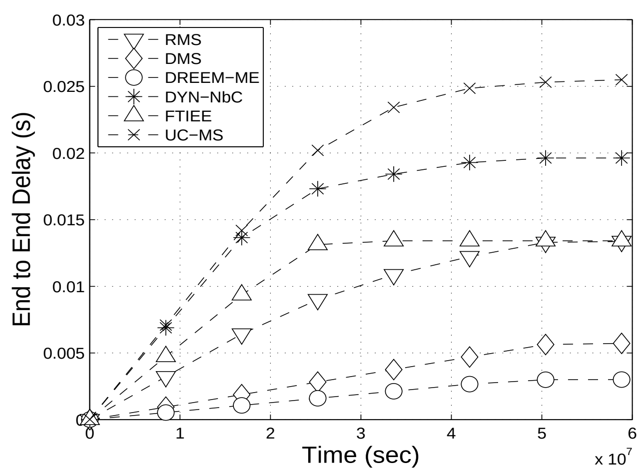


FIGURE 6.14: End to end delay

6.2.5.4 No. of packets dropped

Figure 6.15 shows that those schemes which have high throughput also have high packet drop probability. This model assumes that greater packets sending rate results in greater number of packets drop. DREEM-ME and FTIEE are clustering schemes, where nodes sense the data and periodically transmit it to CH. CH after receiving data from the member nodes aggregate it and send it to the sink. UC-MS has both clustering and as well as MS. First nodes send data to CH, then after receiving data from member nodes CH waits for MS. Chances of packet drop increases in this way. DYN-NbC has need based clustering however, MS is covering 25% directly. In 75% of the network field there is clustering and CHs receive data from member nodes and transmit it to MS. Its packet drop is less than UC-MS in comparison. It is obvious from our proposed schemes that RMS has less packet drop because it receives data from the nodes of maximum dense region on the priority basis. DMS is visiting each region on predefined trajectories which increases the waiting time in some regions, ultimately leading to high packet drop rate.

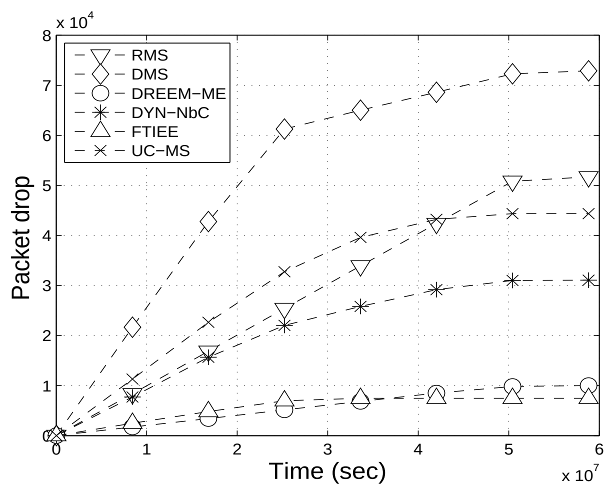


FIGURE 6.15: Packet dropped

6.2.5.5 Path loss

In RMS, the number of sent packets are greater because the MS sets priority to visit dense regions first. In figure 7.10, path loss increases till the nodes in the network sense and transmit. In DMS, path loss is relatively less than that of RMS. Stability period of DMS is greater than all compared schemes i.e. 5×10^7 seconds. In figure 7.10, path loss of DMS linearly increases till 5×10^7 and after that nodes start depleting their energies and path loss curve also alters its behavior.

Both UC-MS and DYN-NbC have clustering mechanism and MS. However, UC-MS shows higher path loss as compared to DYN-NbC because it has uneven clustering and data transmission is only through CHs.

DREEM-ME and FTIEE both are clustering schemes, however, FTIEE has higher path loss because of dynamic clustering, i.e., number of nodes associated with the CH are not fixed.

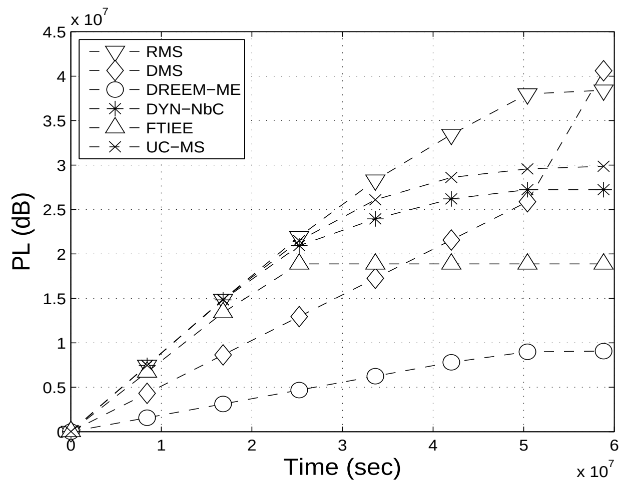


FIGURE 6.16: Path loss

6.2.5.6 Residual energy

It is obvious from figure 6.17 that due to non-continuous transmissions in RMS and DMS the behavior of energy consumption curve is linear. In DYN-NbC, energy is consumed during clustering and CH selection. UC-MS also consumes high energy in cluster formation, CH selection and data aggregation.

6.2.6 Performance metrics - trade-offs

Table 6.2 shows the achievements made by routing the selected routing protocols by paying cost of some other performance metric. DMS achieves higher stability period at the cost of throughput as compared to RMS. However, end to end delay

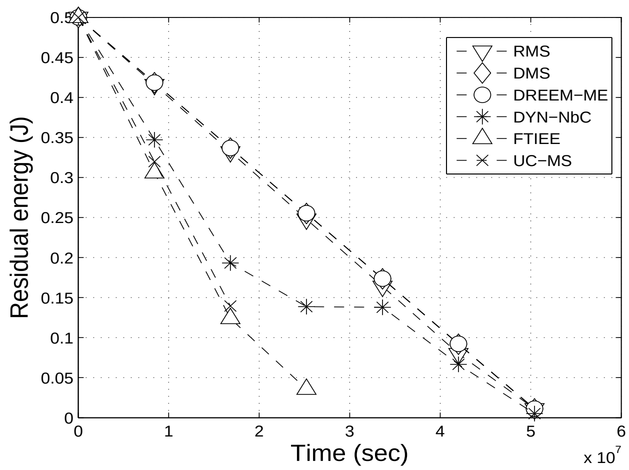


FIGURE 6.17: Residual energy

of DMS is also less than RMS. End to end delay depends upon the number of packets received at sink. As, in RMS larger number of nodes (from dense region) directly transmit data to MS, congestion in network may occur which is the major cause of increased end to end delay. RMS has higher throughput because it gathers data from dense regions on priority basis at the cost of stability period. E2ED of nodes in these schemes is less in comparison to UC-MS, DREEM-ME, DYN-NbC and FTIEE. In UC-MS, nodes first send their sensed data to the CHs and CHs wait for MS to come at their closer stop. Once MS stops at nearer sojourn location, CHs transmit their own data, as well as, received data. Due to high waiting time for MS and multi-hop communication, UC-MS has higher E2ED. DYN-NbC is a clustering scheme with MS. Its working strategy is different from UC-MS. First the whole network field is divided into small sub-regions like RMS and DMS. After that highly dense region where number of nodes are maximum is identified. DYN-NbC's E2ED is less than UC-MS however, greater than DREEM-ME and FTIEE. DMS has higher packet drop rate in comparison to the other compared schemes because MS (in DMS) visits whole network on its turn. RMS receives data from nodes on priority, high node density region nodes send their sensed data earlier, as a result, RMS achieves higher throughput and less packet drop rate.

TABLE 6.2: Performance trade-off made by protocols

Technique	Routing criteria	Distinguished features	Advances achieved	Trade-offs	Remarks
RMS	MS with random trajectory	Random deployment of nodes. Transmit data to MS at minimum distance.	High Throughput, less end to end delay	Less stability, Packet dropped, path loss.	Minimizes energy consumption due to absence of clustering.
DMS	MS with defined trajectory	Randomly deployed nodes with direct transmission to MS on defined trajectories.	Longer stability period, less end to end delay, less path loss	Less throughput.	Minimizes end to end delay, energy consumption is minimum due to direct communication with MS.
DREEM-ME	Static Clustering and Multi-hop	Static clustering, transmission at minimum distance. Uniform random deployment of nodes.	Longer stability period, less end to end delay and packet dropped	Less throughput	Static clustering, transmission at minimum distance. Uniform random deployment of nodes
DYN-NbC	Clustering and MS	Adaptive clustering with sink mobility in specific regions. Random deployment of nodes.	Increased throughput	Min stability period, end to end delay, packet dropped	CH selection is on the basis of LEACH criteria that considers probability only.
FTIEE	Clustering	Fixed clustering on the basis of distance from sink. Machine learning criteria for CH selection. Node deployment is random.	High stability, less packet dropped	Longer end to end delay	Due to fixed clustering and machine learning technique energy consumption of nodes is minimized. However if sink mobility id introduced, further load from the CH can be reduced.
UC-MS	UC and MS	Uneven clustering by following LEACH criteria and MS. Random deployment of nodes.	Enhanced throughput	Stability period, E2ED, Packet dropped.	This protocol uses LEACH criteria for CH selection which do not consider residual energy for CH selection.

6.3 Proposed scheme: GSM

6.3.1 Motivation

Introduction of MS prolongs the network lifetime, however, speed adjustment of the MS need proper attention. Very high speed may lead to improper data collection and very low speed may lead to node's buffer overflow.

In [15], two level heterogenous network was proposed for gathering data through clustering. The CHs, not in range of sink, communicate with their in-range CH to send their gathered data to sink. We consider two level network consisting of normal and advance nodes. Two sinks move on the pre-defined trajectory for data gathering. To save energy, we introduce sleep and awake modes; when MS enters in sensing range of a sensor they are awake and transmit the data to the sink and if sink is out of range they stay in sleep mode.

6.3.2 Network model

WSN is modeled as directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = V \cup S$. $|V| = N$, set of wireless sensor nodes, S is the set of sinks with $|S| = K$. For all $i, j \in \mathcal{V}$, $\exists(i, j) \in \mathcal{E}$ if and only if i and j are within a transmission range r_{tx}. We also assume:

- All the sinks move at the same time means (their movement is synchronous). Sink movement is equally distributed on all locations in every epoch $n = 0, 1, 2, ...$ All the data is transferred to sink before it is further proceed to next location, so, there is no pending data between epochs. In node to sink communication, data delivery is represented by C_j, where $C_j \in 0, 1$, $C_j = 1$ if sink sojourn location is v_j; otherwise $C_j = 0$, $1 \leq j \leq n$.

- $x_{ij} \in 0, 1$, when sink is at location v_j, then $x_{ij} = 1$, where $v_j, 0 \leq i, j \leq n$. x_{ij} is the rate of information.

The sensor nodes form a two level heterogeneous stationary network. Initial energy is E_0 for normal nodes and for advanced nodes it is $(1+\alpha)E_0$. We only consider energy consumption during transmission and reception of the information.

- Network lifetime is defined here as the time interval until first node dies. When the energy of node is depleted, node dies. After the death of first node, instability period of the network starts.

By using above assumptions, we now formulate the optimization problem for network lifetime maximization using MSs on different trajectories with delay tolerant behavior.

$$Maximize\ T = \sum_m t_m \tag{6.13}$$

subject to:

$$\sum_{s \in S} C_j(n) = 1 \qquad \forall j \in V \tag{6.14a}$$

$$\sum_{e^-} f_i(n) - \sum_{e^+} f_i(n) = X \qquad \forall i \in V \tag{6.14b}$$

$$\sum_m t_m\Big(\sum_{i \in N} E^{tm}_{ij} + \sum_{k \in N} E^{rm}_{ki}\Big) \leq E_{initial} \qquad \forall i,j,k \in N \tag{6.14c}$$

$$x_{ij} - R_{ij} \leq 0 \qquad \forall i,j \tag{6.14d}$$

$$x_{ij}, \quad t_i \geq 0 \qquad \forall i,j \tag{6.14e}$$

where $e^- = \{e \in E \mid e = (v,n), n \in V\}$, and $e^- = \{e \in E \mid e = (n,v), n \in V\}$. The function f_i is the amount of data sent over an edge during epoch n. Equation 6.13 defines the objective function which is maximization of network lifetime. Equation 6.14a shows that in one epoch only one sink communicates with a node. Equation 6.14b is a flow constraint, X is the total number of packets in epoch n, which is difference between the received and transmitted flow. Equation 6.14c is the energy conservation equation. Equation 6.14d is the rate constraint which explains that total information rate which flows through the link (i, j) should not exceed the link capacity R_{ij}.

6.3.2.1 Protocol operation

Movement of the sink on predefined trajectory belongs to NP- hard problem. To simplify this problem, we have converted it into a simple geometric case, GSM. Our main objective is to maximize the network lifetime for delay tolerant applications. We logically divide the network field to minimize the communication distance between nodes and sink. The sinks are mobile without having energy constraint. $d_i = |s_k - NUC(v)|$, shows that d_i is the Euclidean distance between sink s_k and Node Under Consideration (NUC). Here, $s \in S$ and $v \in V$ during epoch n. According to basic network calculus delay bound D_i is defined as [82]:

$$D_i = h(\overline{\alpha}_i), \beta_i) \tag{6.15}$$

$$= Sup_{s \geq 0}\{inf\{\tau \geq 0 : \overline{\alpha}_i(s) \leq \beta_i(s + \tau)\}\} \tag{6.16}$$

$$\overline{D}_i = \sum_{i \in v} D_i \tag{6.17}$$

$$\overline{D} = max_{i=1,\ldots,N} \overline{D}_i. \tag{6.18}$$

Where, $\overline{\alpha}_i$ is the sensed input and β_i is service curve. This analysis is for FIFO scheduling at the sensor nodes.

In our model, we divided square field into small square regions as shown in figure 6.18. There are sixteen small squares in a the considered field, twelve out of sixteen are lying on the outer boundary and four are inside this boundary. In the outer boundary, we consider separate area in which one sink gathers data while second sink is supposed to collect the data from the inner region. These two sinks start their journey simultaneously for data collection from the respective regions,

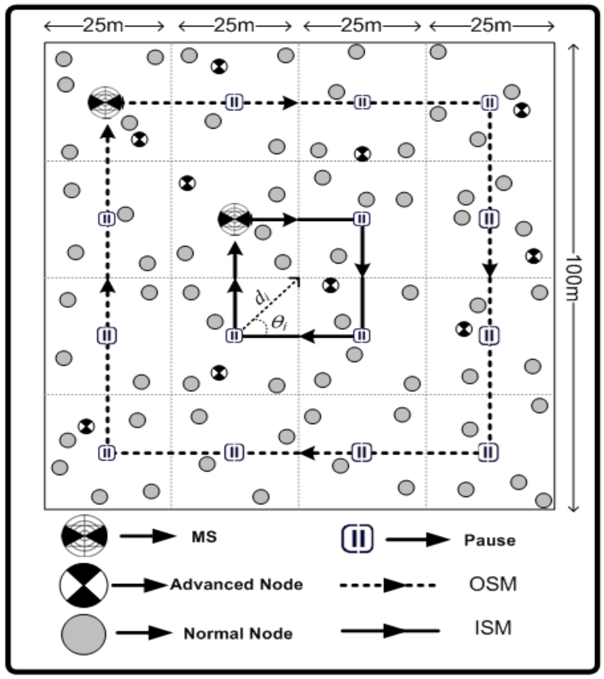


FIGURE 6.18: Network Topology

where the trajectories of sinks are square shaped too. One sink collects data from inner square nodes and other is from outer squares. The trajectories and the sink locations are predefined such that sink stops in the middle of each small square to directly collect data from the nodes. When sink moves forward from the current location, nodes lying in that small square switch to sleep mode and the nodes which come under the new stop region switch to awake mode. The transmission range is $d_i = \sqrt{2}x$, and the distance between two sojourn locations is $d_{min} = 2x$ and that between two different trajectories sojourn location is $d_{max} = 2\sqrt{2}x$, as shown in figure 6.19.

6.3.2.2 Simulation results

We consider a network field of $100m \times 100m$. Total number of deployed nodes in a network are $N = 100$, in which 10% are advanced and remaining are normal nodes. Deployment of nodes in the field is random. We consider joint sinks; one is moving in the inner square trajectory, and the second is in the outer square trajectory.

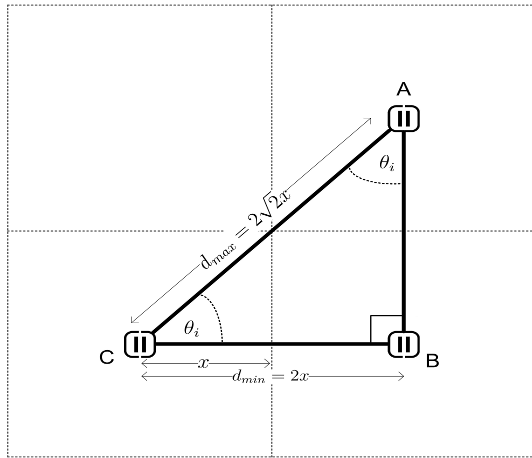


FIGURE 6.19: Depicting d_{max} and d_{min}

The maximum distance of the nodes with the MS related to their partitioned squares is d_{min}. Initially energy assigned to the normal node is $0.5 Joules$ and in advanced nodes it is $1 joule$. We have compared our simulation results with SEP and LEACH.

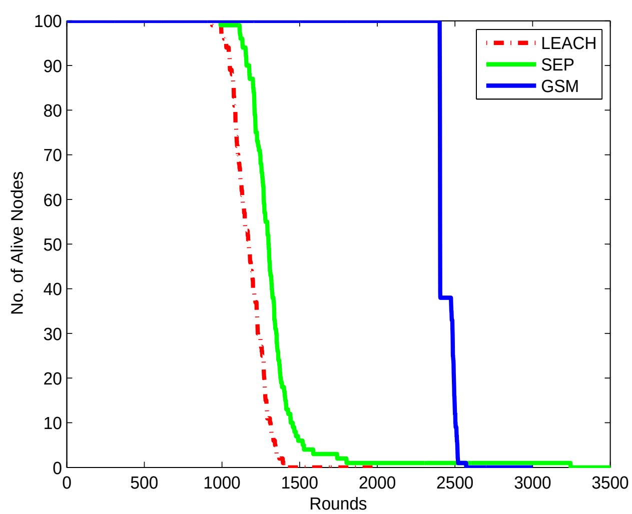


FIGURE 6.20: Number of alive nodes per round

In figure 6.20, we have compared the results of our proposed scheme GSM with SEP and LEACH. First node of the LEACH runs out in 1050 rounds. First node of the SEP depletes its energy in 1000 rounds and after that within few rounds (almost in 1500 rounds) the whole network is dead. The performance of SEP is better than LEACH, its first node dies at 1150^{th} round and after that normal nodes die in few more rounds. The advanced nodes keep alive the system up to 2000th round. SEP performs better than LEACH as it has 10% advanced nodes, and these nodes get maximum chance of becoming CH. Energy is utilized in aggregation, reception and transmission. Due to advanced nodes, SEP performs better than LEACH in terms of network lifetime. Now comparing SEP with our proposed GSM, it is virtually divided in small regions with a defined geometry. CHs are replaced by MSs, here, energy consumption of aggregation and election of CH is saved. As the whole network is efficiently divided into regions and MS observes fixed path and nodes are delay-tolerant, this results in saving energy and prolonging the network lifetime. In GSM, first node dies at 2400th round and the last at 2600th round, its stability period is enhanced as compared to previous schemes. After the death of the first node (in GSM), remaining nodes quickly deplete their energy as compared to others.

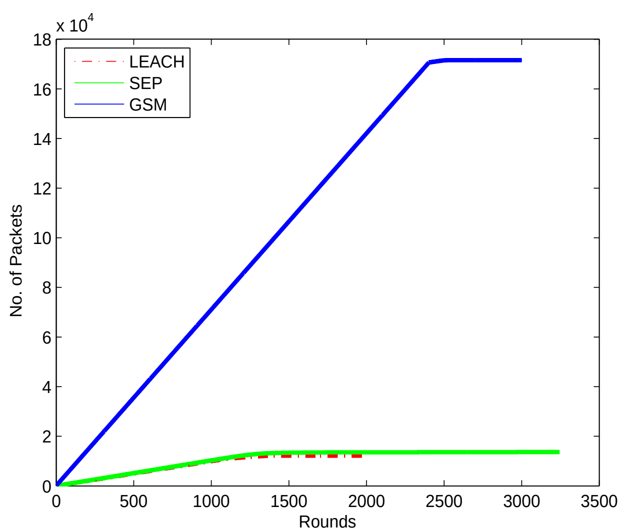


FIGURE 6.21: Throughput of the network

In figure 6.21, results of the throughput are compared. Throughput is defined as total data sent to the sink, sensed by sensors. Heterogeneity increases the stability and ultimately throughput. It also depends upon the link capacity; if all nodes send data at a time, a bottle neck will be created and throughput will decrease, as there are chances of data loss. In joint square sinks, throughput is increased because nodes in the network switch between sleep and awake modes to save energy. As the field is divided in to the small squares, when MS stops at any sojourn location the related square of that stop becomes awake and starts sending sensed data when MS stops at any sojourn location. Due to staying in sleep mode when MS is busy in collecting data from the far stops, nodes minimize their energy consumption. Also nodes save energy by not acting as a relay for data transmission and CH selection. Throughput of LEACH and SEP is close to each other as SEP is extended by adding 10% advanced nodes. Throughput of the joint square sink is significantly greater in stable and as well as in instable region.

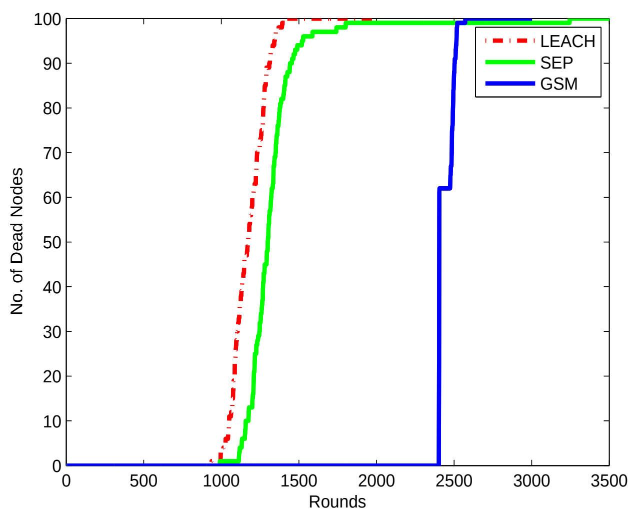


FIGURE 6.22: No. of dead nodes per round

The previously referred figures show that our proposed scheme of joint sink mobility performs significantly better than conventional clustering schemes. As we have used the concept of joint sink mobility in GSM, in which two sinks move inside the sensing field and gather the sensed data from all the deployed sensor nodes. We have defined sensing range of MSs, so, all the nodes in the vicinity of

MSs transmit their data if they lie in the sensing range of that sink. Otherwise, nodes go to sleep mode and save energy. GSM is only applicable for delay tolerant applications; both the sinks move on a squared trajectory within the sensing field. In clustering schemes, sensor nodes send data to their associated CHs and then CHs further transmit the aggregated data to BS. Whereas, in GSM MSs have replaced the CHs which save energy of the nodes, as MS is independent of energy constraint.

6.4 Chapter conclusion

In the proposed RMS, DMS and GSM schemes, the network field is logically divided into small squares to configure MS location. In this way, we have achieved enhanced throughput and prolonged network lifetime. We compared RMS and DMS with DREEM-ME in which the field is divided into concentric circles and depending upon the distance between node and sink, data is either directly transmitted or via multi-hop node. We also compared our proposed schemes with UC-MS and DYN-NbC, these possess clustering as well as MS. Results show that RMS performs better than DMS in terms of data collection from dense regions first and remaining afterwards, while in terms of stability, DMS trajectory shows better performance. In GSM, the network model is two level heterogenous while the nodes switch between sleep and active modes to save energy. Virtual division of the network field for sink locations minimizes the communication distance between nodes and MS. By considering these factors, we enhanced throughput and lifetime of the network. We observes that in LEACH nodes are homogenous and die quickly while in SEP stability period increases due to advanced nodes. In GSM, the sink moves in a controlled pattern. In next chapter sink mobility is implemented in UWSNs, where network field is three dimensional.

Chapter 7

Efficient data gathering in 3D linear UWSN using sink mobility

7.1 Chapter summary

In the proposed scheme, we introduce MS, i.e. Autonomous Underwater Vehicle (AUV) and also Courier Nodes (CNs), to minimize the energy consumption of nodes. MS and CNs stop on specific stops for data gathering, later on CNs forward the received data to MS for further transmission. By the mobility of CNs and MS, overall energy consumption of nodes is minimized. We perform simulations to investigate the performance of proposed scheme and compared with preexisting techniques. Simulation results are compared in terms of network lifetime, throughput, path loss, transmission loss and packet drop ratio. Result shows that the proposed technique performs better in terms of network lifetime, throughput, path loss and scalability.

7.2 Motivation and contributions

Designing an underwater network architecture is hard task due to drastic underwater conditions. The communication model used in underwater is different as compared to the TWSN as given in table 1.1. We proposed a scheme 3D-SM, which has better network lifetime and throughput. Nodes are deployed in the field transmit their sensed data to the MS as these come in its transmission range. We compare it with the existing protocol DDRP [75], that is two dimensional with the radio model for transmissions. For fair comparison, we convert DDRP into three dimensional underwater environment and applied acoustic model for transmissions. The mobility pattern of MS is random in DDRP and there is no restriction that it visits all the regions for data gathering. Due to random mobility it may visit a single region more than once while leaving other regions unattended because the round trip time and number of visits are fixed. In AUV-PN [73], AUV visits pre-identified locations for gathering data. The AUV travels in the network where nodes are deployed, partitions the network into clusters, and provides the partition information to nodes through control packet. Nodes in each cluster selects CH, then CH further divides the cluster into sub-clusters. CH nominates a PN for each sub-cluster for receiving data from the MNs. AUV then starts tour to receive data and acquires the list of PNs from the CHs to collect data.

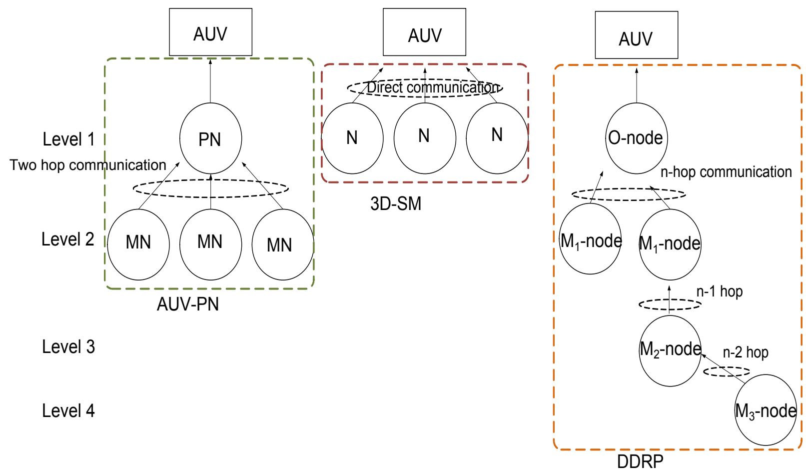


FIGURE 7.1: Comparison of proposed and counter schemes

In these routing protocols, DDRP has coverage problem all the nodes are not able to send their data to MS as it has random trajectory. Also as it is using direct communication and nodes have to wait for their turn. AUV-PN has sink mobility as well as clustering. Nodes have limited battery power and for prolonging network lifetime balanced energy consumption is required. Nodes consume energy in cluster formation and PN selection. Also when PN forwards the data gathered from MN, it consumes more energy. It leads toward quick energy depletion.

We have addressed following challenges in underwater acoustic networks.

-Network energy consumption minimization.

-End to end delay minimization.

In the proposed scheme, nodes directly transmit data to the MS and do not relay data of far away nodes. The scheme is designed in such a way that each node gets a chance to deliver the sensed data. In this way, nodes save their energy that leads to prolonged Network lifetime. To cope with the limitations of underwater transmissions, MS gathers data from RC where it is deployed. CNs collect data from remaining RCs that are not considered in the trajectory of MS.

7.3 Framework and formal definition of the problem

Here we describe the nodes relation with MS or CNs relation. We will also explain network model.

7.3.1 Relationship between nodes and MS

UWSNs can be represented by a directed graph $G = (V, E)$, where V is the set of vertices (nodes) i.e. $\mid V \mid = n$, where, $n = 1, 2, 3, ..., 300$. E are the edges that are links between the nodes. We consider the cuboid field of dimensions $500m \times 500m \times 1000m$ which is further logically divided into four RCs. In one RC, MS gathers the data from the nodes and in rest of the three RCs, CNs are appointed to collect sensed data from the nodes. CNs further forward the received data to MS.

If the node n_i is in transmission radius of MS, it means that n_i is neighbor of MS and data transmission is direct between them. When MS moves to next sink stop, it again finds the neighbor nodes by broadcasting a control packet that contains its location information. n_i is non-neighbor of MS if it is not in the same RC, where MS is deployed. Then it may be neighbor of any C_i. Where C_i belongs to CNs , that moves in each of the remaining linear RC regions and gathers data from n_i' . C_i relays the data of n_i's to the MS.

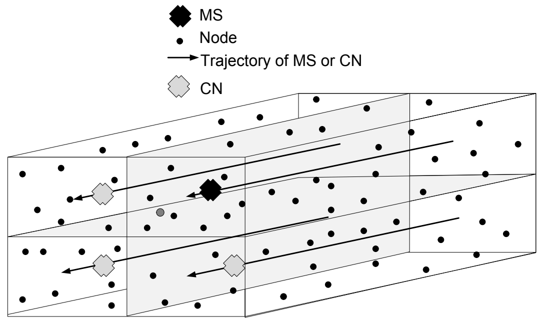


FIGURE 7.2: Network model

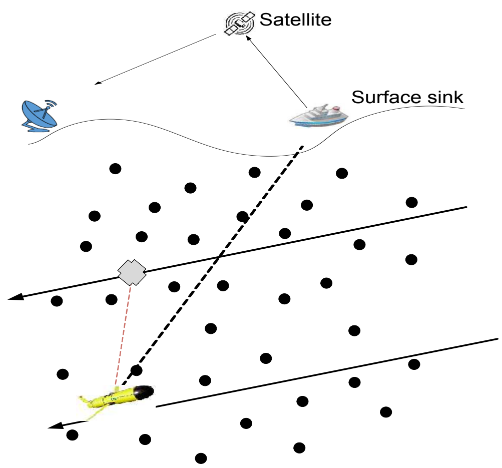


FIGURE 7.3: CN to MS transmission

To support the proposed model a set of linear programming equations is given as follows:

Objective function:

$$Maximizing \quad T \tag{7.1a}$$

$$\text{subject to: } h(i) \leq d(n_i, n_j) + h(j) \qquad \forall i \in N, j = 1, 2, 3, 4 \tag{7.1b}$$

$$T_{max}.f_i \geq t_a \geq T_{min}.f_i \qquad \forall i \in N \tag{7.1c}$$

$$\sum_{j=1}^{4} \sum_{i=1}^{n} d(n_i, n_j) f_i \leq l \qquad \forall i \in N, j \tag{7.1d}$$

$$T.(\sum_{j=1}^{4} \sum_{i=1}^{n} p_{ij}) \leq E_i \qquad \forall i \in N, j = 1, 2, 3, 4 \tag{7.1e}$$

$$E_i(t_a) \geq E^{tx}_{(min)} \qquad \forall i \in N \tag{7.1f}$$

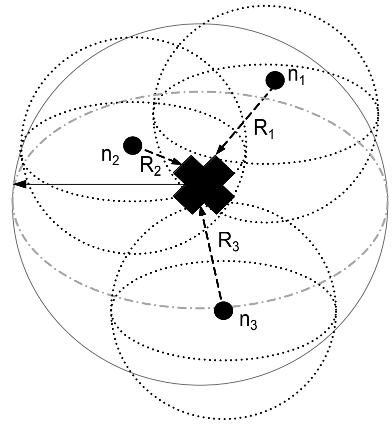


FIGURE 7.4: MS is neighbor of n_i nodes

$$f_{ij} \leq f_{ij}^{max} \tag{7.1g}$$

$$t_i, f_i \geq 0 \qquad \forall i \in N \tag{7.1h}$$

where, T is the network lifetime. Eq. (7.1a) defines the objective function, while eq. (7.1b) shows the heuristic for finding minimum distance between neighbors and non-neighbors. In eq. (7.1c) T_{min} shows the minimum pause time of MS at sink stop. Eq. (7.1d) shows that MS tour will not exceed the l. Energy conservation constraint is represented in eq. (7.1e), that means total energy that nodes consume during the network lifetime can not exceed the initial energy. Transmission of data depends upon the residual energy of node, if it is equal to the minimum energy required for transmission that is represented in eq. (7.1f).Eq. (7.1g represents the flow constraint through physical link. It shows that if flow from i to j exceeds the upper bound f_{ij}^{max}, then it results in packet loss / packet drop.

7.3.2 Graphical analysis

In our proposed scenario, there are two paths for data transmission from nodes to MS. Direct transmission from node to MS and via CN. End to end delay is greater when MS receives data from node via CN. End to end delay is minimum when nodes send data through direct transmission. The total end to end delay denoted by D is combined delay of direct $(D - MS)$ and multi-hop transmission $(D - CN)$.

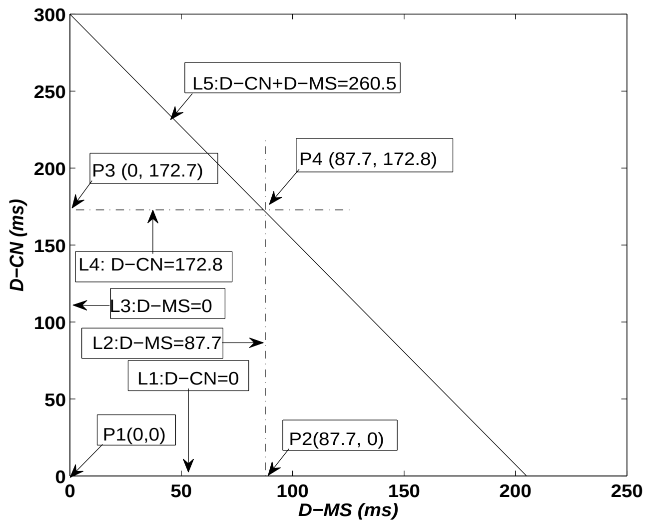


FIGURE 7.5: Delay: feasible region

We defined an objective function:

$$Minimize \quad D \tag{7.2}$$

$$\text{subject to: } D = (D - MS) + (D - CN) \tag{7.3}$$

$$87.7 \leq (D - MS) + (D - CN) \leq 172.8 \tag{7.4a}$$

$$0 \leq (D - MS) \leq 87.7 \tag{7.4b}$$

$$0 \leq (D - CN) \leq 172.8 \tag{7.4c}$$

$$0 \leq (D - MS) + (D - CN) \leq 260.5 \tag{7.4d}$$

The eq. 7.5a aims to minimize end to end delay of the network. Eq. 7.3 defines the nature of delay i.e, objective function and two dimensional linear programming problem. Constraints in eq. 7.4a provide lower and upper bounds of the path respectively. Constraints defined in eq. 7.4b and 7.4c defines upper bounds of $D - MS$ and $D - CN$ independently. Eq. 7.4d defines upper and lower bounds of the network jointly considering both types of delays. Figure 7.5 shows the set of feasible solutions. There are lines, $L1, L2, L3$ and $L4$ intersecting each other and the region form by their intersection is the set of all feasible solutions. Minimum value of each vertex can be obtained as:

at $P1(0, 0) : D = 0ms$

at$P2(87.7, 0) : D = 87.7ms$

at $P3(0, 172.8) : D = 172.8ms$

at $P4(87.7, 172.8) : D = 260.5ms$

The minimum value of D is $0ms$ which shows that transmissions are not started yet. It is initialization phase. The next value of D is $87.7ms$. It indicates direct transmission to MS. Similarly, the next value $172.7ms$ for multi-hop transmission through CN. Last value is maximum delay i.e, $260.5ms$, all values lie within this bound. This shows that values of delay at each point lies in within the boundaries of illustrated region.

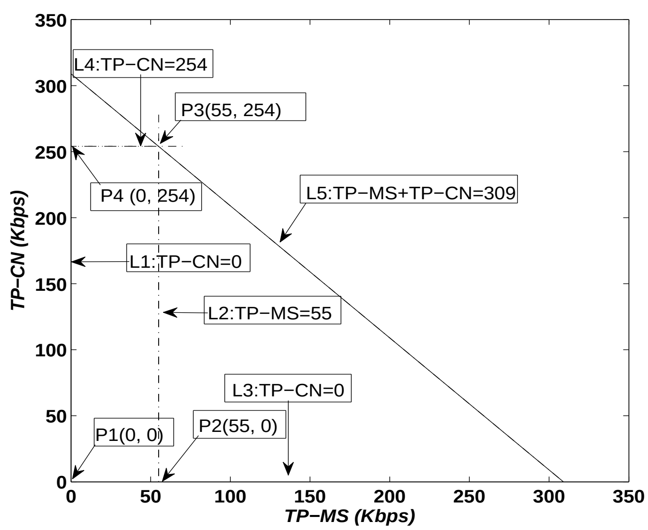


FIGURE 7.6: Throughput: feasible region

During the network lifetime, MS and CNs move in the defined RC and collects data periodically, that reduces delays and increases throughput. In figure 7.6 feasible region for throughput is shown, it is represented with units Kbps. ($TP = (TP - MS) + (TP - CN)$)

$$Maximize \quad TP \tag{7.5a}$$

$$\text{subject to: } 0 \leq (TP - MS) + (TP - CN) \leq 300 \tag{7.5b}$$

$$0 \leq (TP - MS) \leq 55 \tag{7.5c}$$

$$0 \leq (TP - CN) \leq 245 \tag{7.5d}$$

According to the bounds provided in eqs. 7.5b, 7.5c and 7.5d; figure 7.6 shows the intersecting lines $L1, L2, L3$ and $L4$, resulting in a bounded region that shows the set of feasible solutions. Values on each vertex are obtain as:

at $P1(0,0) = 0Kbps$,

at $P2(55,0) = 55Kbps$,

at $P3(55,245) = 55 + 245 = 300Kbps$,

at $P4(0,245) = 245Kbps$

Validity of feasible region is proved. The total throughput during a trip of MS and CN is lying within the boundaries of illustrated region.

7.3.3 Delivery probability

In the proposed scheme, we classify nodes into two categories: neighbors of MS and non-neighbors of MS. Their delivery probability is given as $del_{prob} = \frac{pkt_d}{pkt_f}$. Where, pkt_d are successfully delivered packets by node and pkt_f are packets sent by the node.

We ignore water currents in our scheme and assumed that nodes present in the network are static.

7.3.4 Attenuation and propagation delay

Unlike terrestrial WSNs, attenuation in UWSNs does not only depend on the link distance but also on signaling frequency f i.e. $A(d, f)$, where A is attenuation function. After attenuation, the Signal to Noise Ratio (SNR) of the received signal is $\rho(d, f)$ [84]. For distance "d" between source node and the MS (destination) at a frequency $f(kHz)$ with spreading coefficient k, Urick in [85] defined attenuation eq $A(d, f) = A_0 d^k a^d(f)$. Where A_0 denotes normalization constant and $a(f)$ is absorption coefficient that is described by Throps formula [86].

$$10log_a(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4200+f} + \frac{2.75f^2}{10^4} + 0.003 \quad if \quad f > 0.4 \tag{7.6}$$

and

$$10log_a(f) = 0.002 + \frac{0.11f}{1+f} + 0.011f \quad if \quad f < 0.4 \tag{7.7}$$

it is calculated in dB/km.

End to end delay model in [87] is used to calculate the propagation delay i.e.

$$T_p = \frac{s}{v} \tag{7.8}$$

where s is distance between sender and receiver node and v is speed of acoustic signal which is given as

$$v = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + (1.333 - 0.126t + 0.009t^2)(S - 35) + 16.3z + 0.18z^2 \tag{7.9}$$

where $t = T/10$, T is the temperature in ^0C, S is salinity in ppt, and z is the depth in m.

7.3.5 Acoustic channel noise

Ocean medium is different than air medium in WSNs in terms of impedance. In acoustic channel, signal is affected by different noises. We take into account turbulence (N_t), shipping (N_s), wind (N_w) and thermal noise (N_{th}). Authors in [88] modeled these noises by Gaussian statistics, given as:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{7.10}$$

where,

$$10logN_t(f) = 17 - 30logf$$

$$10logN_s(f) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03)$$

$$10logN_w(f) = 50 + 7.5\sqrt{w} + 20logf - 40log(f + 0.4)$$

$$10logN_{th}(f) = -15 + 20logf$$

here, s is shipping activity factor and it ranges $0 \leq s \leq 1$ and $0 \leq w \leq 10(m/s)$ wind velocity.

7.3.6 Energy consumption model in UWSNs

Nodes deployed in the underwater network field are powered by batteries. Energy consumed in sensing and processing data is negligible as compared to the data transmission and reception. Transmission power depends upon the distance and transmission range. With the propagation model, we estimate the transmit power for specified signal-to-noise ratio (SNR). We use energy consumption model for acoustic communication given in [89]. SNR equation for passive sonar is calculated in eq 7.11

$$SNR = SL - TL - NL + DI \geq DT \tag{7.11}$$

where, SL represents source level, transmission loss is transmission loss, NL is noise level of receiver and the environment. Directive index is denoted by DI. Sonar's detection threshold is DT. Transmission loss for nodes in underwater environment is calculated in eq. 7.12 by Thorp model in [90], i.e.

$$TL = 10log(d) + \alpha d \times 10^{-3} \tag{7.12}$$

where, d denotes the distance between sender and receiver, and α is absorption coefficient. In eq. 7.11, noise loss is calculated by eq. 7.10. SL can be calculated from eq. 7.11:

$$SL = SNR + TL + NL - DI \tag{7.13}$$

Transmitted signal intensity is calculated as

$$I_T = 10^{SL/10} \times 0.67 \times 10^{-18} \tag{7.14}$$

and transmitted power by source is

$$P_T(d) = 2\pi \times 1m \times H \times 10^{SL/10} \times 0.67 \times 10^{-18} \tag{7.15}$$

Energy required for the transmission of k bits over a distance d is given as:

$$E_{tx}(k,d) = P_T(d) \times T_{tx} \tag{7.16}$$

where, T_{tx} is time in seconds that k bit takes to reach destination by covering d distance.

7.4 Network model and description

Consider a network with N numbers of battery operated wireless nodes, they are randomly deployed in the field and they will remain stationary afterwards. All the nodes in the network have equal sensing range and equal amount of initial energy. A node perform four major tasks: sensing, computing, reception and transmissions. In UWSNs, nodes use acoustic communication for data transmission and it has large propagation delay. To save energy, sleep awake mechanism can be introduced in the network. However due to long propagation delay, nodes may not be able to receive control message from MS and get active immediately. In our proposed scheme, nodes stay active till their death. UWSNs are different from terrestrial WSNs in term of low communication bandwidth and ocean current. This scheme follows the following two steps:

Algorithm 1 Identifying neighbors and non-neighbors

1: Each node and MS broadcast a control packet.
2: If n_{i0} and MS receive each others packet and corresponding "acknowledgement", then these add each other to the neighbors list.
3: If n_{i1} receives "acknowledgement" from C_i instead of MS, then it updates its neighbor list with C_i and it is non-neighbor of MS.

Association phase:

i- MS has the information of its location (X_n, Y_n, Z_n), where $n = 1, 2, 3, 4$.

ii- MS collects data from in range neighbors by calculating distance, i.e., $d(n_{i0}) = \sqrt{(x_{i0} - X_n)^2 + (y_{i0} - Y_n)^2 + (z_{i0} - Z_n)^2} \leq R$, where, n_{i0} is single node with location coordinates (x_{i0}, y_{i0}, z_{i0}), and R is radius of sensing range of MS.

iii- Nodes that are non-neighbor of MS find the C_i for data forwarding. They find minimum distance C_i, $d(n_{i1}) = \sqrt{(x_{i1} - x_{ci})^2 + (y_{i1} - y_{ci})^2 + (z_{i1} - z_{ci})^2} \leq r$, where, n_{i1} is single node with location coordinates (x_{i1}, y_{i1}, z_{i1}), i.e., non-neighbor of MS and r is the sensing and transmission radius of C_i.

Algorithm 2 Defining edges for data packet forwarding

1: Each node which is neighbor of MS sends data through direct transmission.
2: Non-neighbors of MS find the C_i, which collect their data and forward it to MS.
3: C_i has no energy constraint, data transmissions occur at minimum distance.

iv- A node sends the sensed data to MS directly if $d(n_i) \leq R$, otherwise, they wait until MS arrives at the nearest stop. Same condition is for those nodes which send their data to C_i, if $d(n_i) \leq r$.

Collection phase: After the start of network operation, all nodes are in active mode and sense data from the field. MS broadcasts a control packet $I_c(n_i, d(n_i), t_i, R)$, where I_c is a control packet, n_i is current node id, $d(n_i)$ is the distance between node and MS. t_i is time slot allocated to n_i for data transmission, R is the transmission radius of MS.

Nodes that do not receive the control packet from MS in certain time t. They receive control packet from C_i i.e. $i_c(n_{i1}, d(n_{i1}), t_{i1}, r)$, where, i_c is control packet, n_{i1} is the current node id neighbor of C_i. $d(n_{i1})$ is the distance between nodes and CN. r is transmission radius of node.

7.5 Simulation results

In this section, we evaluate the performance results of 3D-SM.

7.5.1 Performance metrics - definitions

Definitions of the performance parameters are given in chapter 3 section 3.5.1. Whereas for network lifetime in this scheme is defined as the time from the start of the network till the death of first node. It is measured in unit of time i.e. seconds.

7.5.2 Performance metrics - discussions

For simulations we consider $500m \times 500m \times 1000m$ field. 300 nodes are randomly deployed in the network with same initial energy i.e, $70J$. Transmission radius of MS is $70m$ in each scheme. DDRP has multi-hop transmissions for data delivery to MS, which is collecting data from the nodes and has random trajectory. In 3D-SM, MS collects data from nodes directly and it moves periodically in the field. The region far from MS has CNs that help in avoiding multi-hop communication and collects data from nodes and send it to MS at minimum distance.

7.5.2.1 Network lifetime

3D-SM balances the load of nodes and results in longer network lifetime. Exponential node depletion shows that energy consumption of the nodes is balanced and after the death of first node, nodes start depleting the energy. This scheme avoids multi-hop transmissions in order to save the energy of nodes. MS and CNs receive data from nodes and then CN further transmit received data to MS. In terms of network lifetime, $3D - SM > AUV - PN > DDRP$. This analysis shows that AUV-PN consumes more energy in formation of clusters and in selection of CHs that results in shorter network lifetime. However, DDRP and AUV-PN both have imbalanced energy consumption that depicts from the figure 7.7. Nodes which are selected as CHs have shorter lifetime because these relay the data of MN. The selection criteria of CH is based on LEACH protocol, which depends upon probability. This is the major flaw of LEACH protocol, there exists no check on residual energy, many authors addressed this issue (ref. SEP, DEEC, etc.). While in DDRP, there is no set pattern of MS trajectory that it will cover

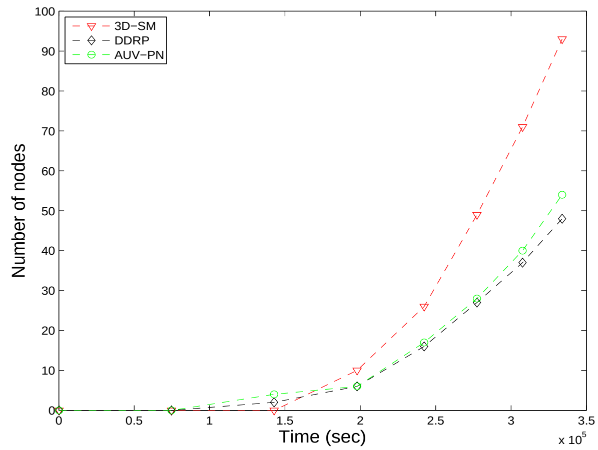


FIGURE 7.7: Network lifetime

the whole network. Its mobility is random, it may visit same region twice in its data collection tour, this leads to imbalanced transmissions as shown in figure 7.7.

7.5.2.2 Throughput

In figure 7.8, throughput is shown, 3D-SM performs better due to longer network lifetime and mobility pattern of MS. CNs frequently receive data from the nodes and send these data to MS, this results in greater throughput. AUV-PN has CH to collect data from MNs and forward the received information to the sink. Each node sends its data during a round to sink via CH. While in DDRP due to random mobility, MS may not receive all the information from the field. DDRP achieves higher network lifetime as compared to the AUV-PN however at the cost of throughput. Initially, the behavior of the plot is linear as in all three protocols all the nodes are alive.

7.5.2.3 Packet dropped

When number of transmissions and receptions increases the packet drop ratio also increases due to collisions. In simulation, we used Random uniformed model [83], where packet drop is related to bad link status through which it is propagated. If

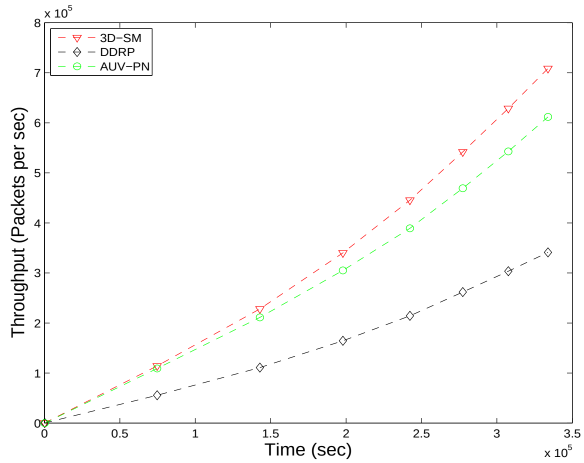


FIGURE 7.8: Network throughput

the link status is good sink successfully receives a data packet, on the other hand if the link status is bad, packet is dropped. In our simulations we set the 30% probability of bad link status that means $p_{bad} = 0.3$ and $p_{good} = 0.7$. CNs gather data and deliver to MS when these have more data to deliver in limited time then packet drop ratio increases. Dense networks have higher packet drop ratios as compared to the sparse ones. In figure 7.9, packet drop ratio of 3D-SM is greater than DDRP because it has more packets to transmit to sink, probability of packet drop also increases. In AUV-PN, there is more probability of packet drop as this

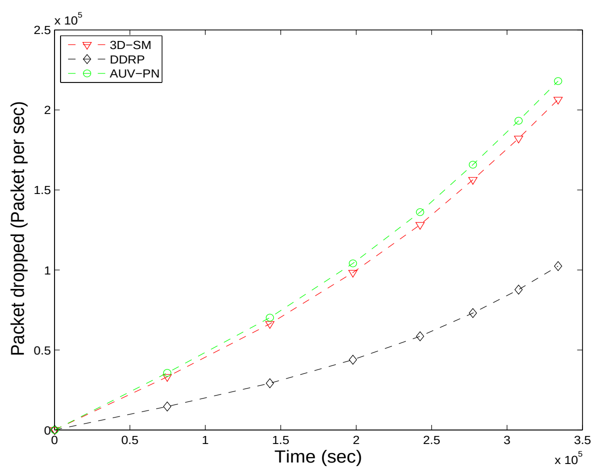


FIGURE 7.9: Packet dropped

protocol engages two hop transmission; MN's data through CH to the MS. Also, it depends upon the number of packets sent to sink, DDRP's throughput is less in comparison with 3D-SM.

7.5.2.4 Path loss

During the transmissions in acoustic model energy loss occurs along the propagation paths. The primary mechanisms for the energy loss are: geometric spreading, absorption loss and scattering loss. Geometric spreading is defined as sound wave moves away from the node, the area that the sound energy covers becomes larger and as a result sound intensity decreases. Underwater medium for propagation is dense as compared to the terrestrial, when an acoustic signal propagates from source node towards the MS and the distance between them is long, power loss is caused by the geometric spreading. Which is directly proportional to the square of the distance. When source node transmits the signal it may be converted to other forms and absorbed by the medium. In case of acoustic signals, the absorption coefficient is calculated in [71]. Scattering is a physical process where non-uniformities in the medium like particles and bubbles, force signal to deviate from its trajectory. Due to dense underwater channels there are more chances of scattering. Scattering causes path loss as well as end to end delay. In figure 7.10, path losses are shown. In 3D-SM, path loss is less in comparison. Whole plot of 3D-SM is not changing drastically as AUV-PN and DDRP. AUV-PN is a cluster based with MS routing protocol, path loss linearly increases with higher rate in comparison up till network lifetime. After that around $70,000 sec$ its behavior is slightly varying, however when number of dead nodes is increased path loss also increases because network becomes sparse. In DDRP, during network lifetime there is slight increase in path loss, however, after the death of first node path

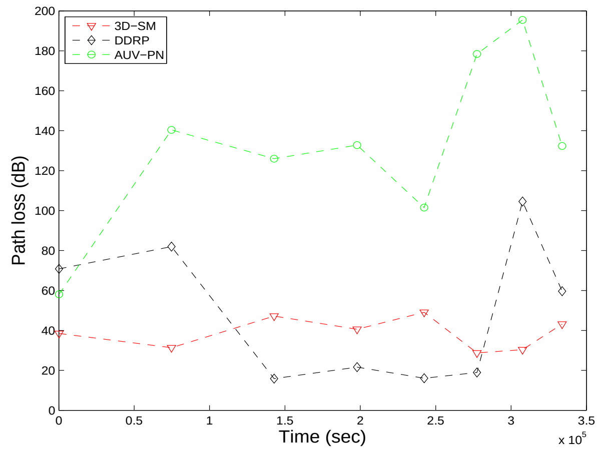


FIGURE 7.10: Path loss

loss decreases because nodes start dying, that leads to an increasing time abrupt change in path loss when the network is sparse.

7.5.2.5 Transmission loss

Transmission loss is defined as decrease of the signal intensity through the path from the sender node to the receiver node. There had been developed diverse empirical expressions to measure the transmission loss. Thorp formula defines the signal transmission loss (eq. 7.12). Transmission loss for the proposed scheme is

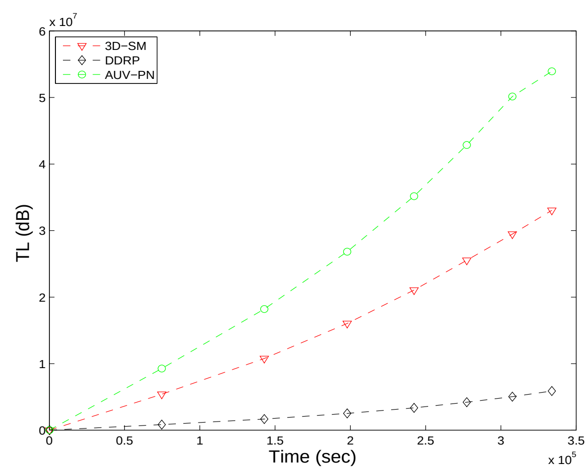


FIGURE 7.11: TL of the network

shown in figure 7.11. The results show that transmission loss of 3D-SM is greater than DDRP. In 3D-SM, number of transmission are greater, transmission loss depends upon the distance between the sender and receiver. In this scheme the transmissions are direct and distance varies from minimum value to maximum (transmission range). The nodes far from the MS also directly send data that increases the transmission loss in the scheme. In DDRP, data from source to receiver is sent through multi-hop transmission at minimum distance. This decreases the transmission loss.

Transmission loss of AUV-PN is higher due to clustering. It is the cost paid to achieve better throughput and less delay.

7.5.2.6 End to end delay

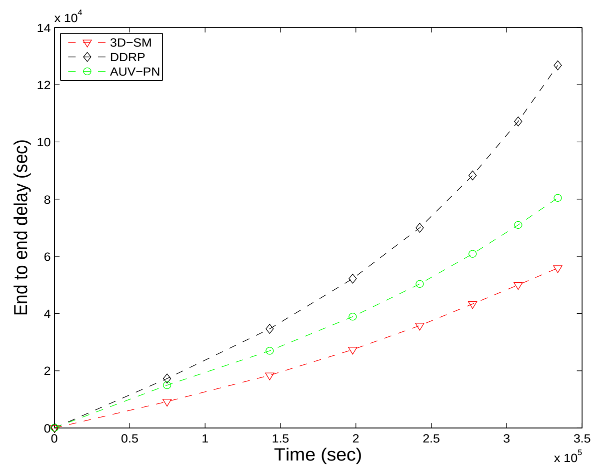


FIGURE 7.12: End to end delay

End to end delay depends upon speed of acoustic signal and the transmission distance. Here, s denotes the distance between source node to the MS/ CN, speed of acoustic signal varies from $1450m/s$ to $1500m/s$ depending upon the depth of water. As $t = s/v$, end to end delay directly proportional to the communication distance. In figure 7.12, DDRP has greater end to end delay because nodes have to wait until MS arrives at nearby stop to receive data otherwise data is forwarded via multi-hopping due to random mobility of MS. In AUV- PN, for data transmission nodes have to transmit the sensed data to the CH.

CH forward the received data to the MS, this procedure increases the delay. In our proposed scheme 3D-SM, MS gathers data form the nodes after a regular interval. In rest of the regions, CNs transmit the collected data to MS which leads to relatively lower end to end delay.

7.5.3 Performance metrics - Trade-offs

3D-SM has increased throughput, however, at the cost of increased packet dropped. The transmission pattern here is direct, after sensing data, nodes wait for MS or CN to send it data. In this way end to end delay is minimized by introducing an efficient tour of MS as well as CNs. The presence of CN is contributing for network lifetime maximization, however at the same time it is reason of transmission loss in 3D-SM. We applied random uniform model for calculating the packet drop, where packet drop is directly proportional to the throughput , higher the throughput higher the packet dropped ratio.

DDRP minimizes transmission loss and path loss at the cost of reduced throughput, increased end to end delay and reduced network lifetime. DDRP has long end to end delay due to the random trajectories of MS. Also, there is no restriction that MS will gather data from all nodes in a tour.

AUV-PN is a cluster based routing protocol in which PN receives data from MN and sends it to AUV. Its network lifetime is less as compared to the rest of the schemes because node consume surplus energy in clustering process. AUV-PN minimizes delay and prolongs network lifetime at the cost of transmission loss and path loss.

7.6 Scalability analysis

Our proposed 3D-SM and the existing AUV-PN and DDRP are simulated by varying the number of nodes in the network ranging from 200 to 1000. In figure

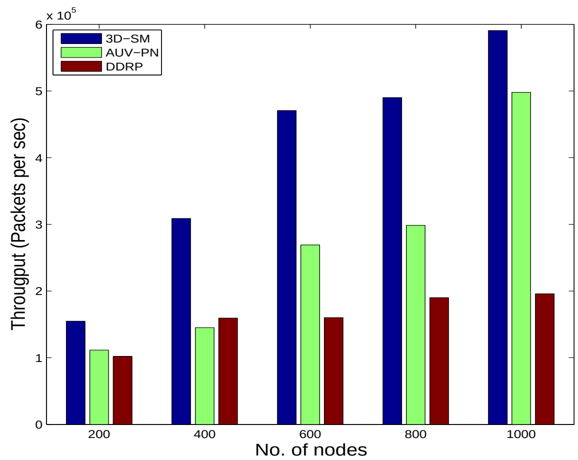


FIGURE 7.13: Throughput comparison with different no. of nodes

7.13 behavior of throughput of three routing protocols with different number of nodes is shown. By increasing nodes in the network with same dimensions SM-3D and AUV-PN, throughput has increasing behavior. While in DDRP there is a slight change in the throughput. DDRP supports multi-hopping, with the increase in number of nodes, maximum nodes send their data through multi-hoping that increases the transmission losses (figure 7.14), path losses (figure 7.15) and increased end to end delay (figure 7.16). While AUV-PN and SM-3D are receiving data directly from nodes, end to end delay may increases relatively.

Figure 7.14 shows the transmission losses, with the change in the number of nodes. In SM-3D transmission losses linearly increase. In AUV-PN and DDRP, transmission losses exponentially increase with increased node density. Path loss with increased node number is shown in figure 7.15. There is slight variation in path loss value in 3D-SM and AUV-PN, while in DDRP by increasing number of nodes

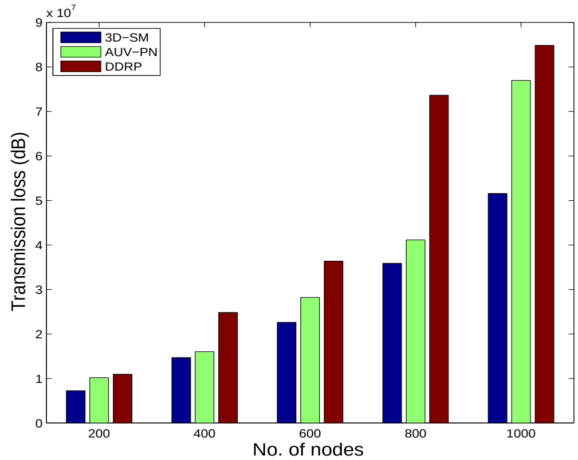


FIGURE 7.14: Transmission loss

in the network path loss also increases exponentially. As the node density in net-

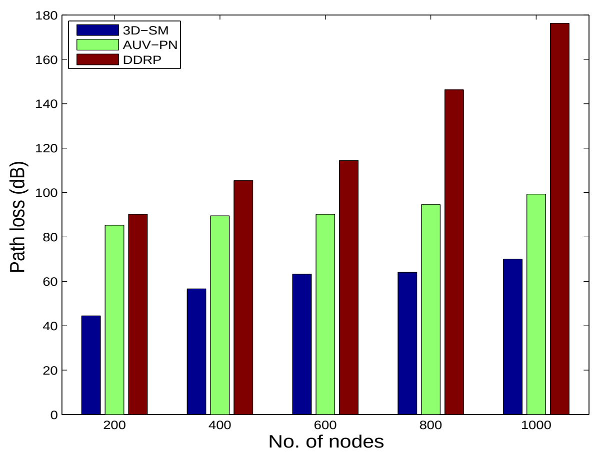


FIGURE 7.15: Path loss

work increases end to end delay of 3D-SM increases as compared to AUV-PN. In AUV-PN more clusters are formed and also number of PNs increases and load on PNs is managed in terms of end to end delay. While in 3D-SM number of MS and CNs is fixed, by increasing number of nodes, MS and CNs get burdened and delay increases.

In DDRP end to end delay exponentially increases because of multi-hopping. We

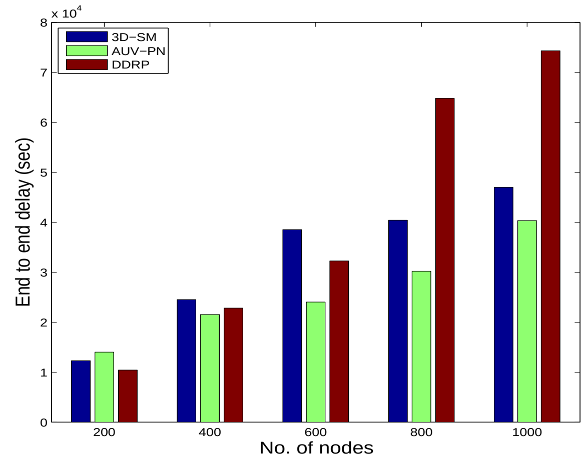


FIGURE 7.16: End to end delay

concluded from this analysis that 3D-SM is more scalable as compared to AUV-PN and DDRP.

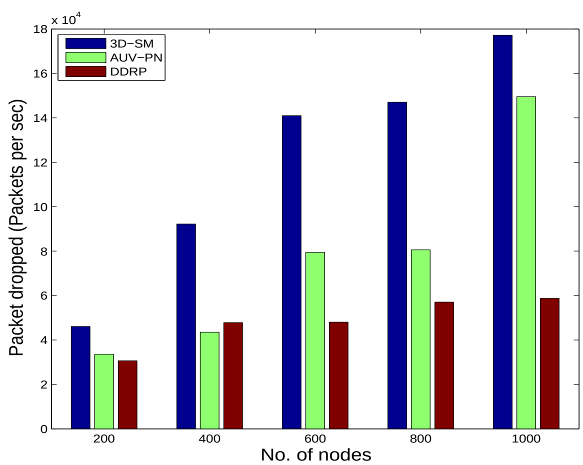


FIGURE 7.17: Packet drop ratio

7.7 Chapter conclusion

In this chapter, we have proposed an efficient routing protocol, i.e. 3D-SM for UWSNs. It is implemented on linear network. To minimize the energy consumption of nodes whole field is logically divided into RCs and also MS and CNs are deployed. The mobility of MS and CNs increases the network lifetime and also minimizes delays. In order to validate our scheme, we compared it with selected existing schemes. Simulation results show that 3D-SM improves stability period approx. 60% than DDRP and 50% than AUV-PN. Also throughput, path loss transmission loss and packet drop ratio of proposed scheme is better than existing compared protocols.

Also, we presented scalability analysis that shows that 3D-SM is scalable.

Chapter 8

Conclusion and future work

8.1 Conclusion

In static sink based WSNs, nodes near sink quickly deplete their energy resulting in premature disconnection from the network. To alleviate this problem, balanced energy consumption strategies are needed. MS is one of the most effective means to minimize/balance energy consumption of the network nodes while maximizing data gathering. In this dissertation, we have comprehensively overview and evaluated existing routing strategies that involve MS(s) in WSNs and UWSNs. The evaluation enabled us to identify key control parameters whose proper tuning significantly facilitates achievement of the desired objective(s).

In this dissertation, we have presented sink mobility based routing protocols for WSNs. These presented protocols cover both reactive and proactive domains in homogeneous and heterogeneous simulation environments. For example: AM-DisCNT and iAM-DisCNT are proactive protocols for homogeneous WSNs; HEER and MHEER are reactive protocols for homogeneous WSNs; BEENISH, iBEENISH, MBEENISH and iMBEENISH are proactive protocols for heterogeneous WSNs. In AM-DisCNT, logical clustering and fixed number of selected CHs improved the network lifetime. However, at the cost of reduced throughput. iAM-DisCNT uses two MSs that significantly improved the network lifetime and throughput. AM-DisCNT has approx. 32% whereas, iAM-DisCNT has approx. 48% improved the stability period as compared to LEACH and DEEC routing protocols. Similarly, the hybrid nature of HEER minimized the energy consumption of nodes to some extent. However, HEER selects random number of CHs in each iteration that lead to uneven cluster size. MHEER uses static clustering, fixed number of selected CHs in each iteration, and MS. Thus, MHEER's performance is better than that of the HEER. HEER-SM has approx. 38%, MHEER has approx. 40% and MHEER-SM has approx. 46% better stability period than HEER.

BEENISH contributes in network lifetime prolongation by introducing four types of nodes on the basis of initial energy; normal, advanced, super and ultra super. A problem with this technique is the frequent selection of high energy nodes to act as CHs. iBEENISH dynamically adjusts the CH selection probability to solve this problem. Sink mobility versions of BEENISH and iBEENISH yield further improvements in terms of network lifetime and throughput. Where, iMBEENISH improved stability period approx. 15% than MBEENISH, 27% than iBEENISH and approx. 37% than BEENISH. We have investigated different sink mobility trajectories that include both defined and random ones. In defined trajectories, we investigated sink mobility on a defined path as well as random trajectories. Based on the findings of our investigation, we proposed 3D-SM for UWSNs. This protocol showed significant improvement towards our desired objectives due to sleep and active modes of nodes, and incorporation of CNs and AUV in the network. Simulation based validation of all the proposed schemes justify their relative effectiveness in terms of the selected performance metrics. Network stability in 3D-SM is improved approx. 60% than DDRP and 50% than AUV-PN.

8.2 Future work

In this dissertation, we have not considered wide area networks and the computational cost of trajectories. There is considerable opportunity to extend the current work in both of these areas. Since our contributions are only simulation based, real time experimental test bed development to test these protocols is also a potential research area. Moreover, the findings of diversities in simulation and real time development will be highly appreciated by the research community. As the sink has no energy and computational constraints, usage of machine learning techniques to find/choose optimal MS location will significantly improve network performance. Finally, it will be more interesting to consider sink mobility with node deployment as a joint optimization problem.

Chapter 9

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