On Energy Efficient Routing Protocols for Wireless Sensor Networks

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Certificate

This is to certify that the work in the thesis entitled ***On Energy Efficient Routing Protocols for Wireless Sensor Networks*** submitted by ***Suraj Shrama*** is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of *Doctor of Philosophy* in *Computer Science and Engineering.* Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

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Abstract

The sensor nodes communicate together by wireless techniques, and these communication techniques are handled by routing protocols. The resource limitation and unreliable low power links between the sensor nodes make it difficult to design an efficient routing protocol. The sink may be either static or mobile in the network. In many scenarios, static sink causes hotspots, where the sensor nodes near to the sink die out soon due to transmission overhead. On the other hand, the mobile sink improves the lifetime of a network by avoiding excessive transmission overhead on the nodes that are close to the sink. Further, an attempt is made to resolve the issues of sensor nodes and sink mobility by proposing energy-efficient routing techniques for wireless sensor network.

A multipath routing protocol (MRP) is proposed, which reduces the control overhead for route discovery and increases the throughput of the network. The proposed multipath routing protocol is designed to improve the lifetime, latency and reliability through discovering multiple paths from the source node to the sink. MRP is a sink initiated route discovery process, where source node location is known. In MRP, one primary path and number of alternate paths are discovered.

The sink may receive redundant data due to densely deployed sensor nodes. Clustering the sensor nodes is an effective way to reduce the redundancy. The cluster head aggregates the cluster members' data before transmitting it to the sink. A cluster based multipath routing protocol (CMRP) is proposed, where the clustering technique reduces the data traffic in the network, and multipath technique provides the reliable path.

Although, the hotspot problem can be resolved with mobile sink, it makes the network dynamic. A tree-based data dissemination protocol with mobile sink called TEDD is proposed to overcome the above problems. TEDD manages the mobility of the sink and balances the load among the sensor nodes to maximize the lifetime. A sensor node initiates the tree construction and becomes the root node of the tree. Sensor nodes can send the data to the sink using this tree. It

has been observed that the TEDD is a robust and energy-efficient protocol in the mobile sink environment.

The proposed dense tree based routing protocol (DTRP) is an extension of TEDD. The objectives of DTRP are to minimize the control overhead and reduce the path length. Both the objectives are achieved by reducing the number of relay nodes in the tree structure. DTRP resulted in, increased lifetime and reduced end-to-end latency.

A clustered tree based routing protocol (CTRP) is designed to reduce the data traffic in the network and efficiently manage the sink mobility. The traffic is reduced by the cluster head, which uses the aggregation technique. The number of cluster heads is restricted to the number of grids present in the network. The CTRP efficiently manages the load among the sensor nodes. The tree is constructed in the network using the cluster heads as vertices. The data can be transmitted to the sink through the tree structure. The CTRP is compared with the TEDD and DTRP in terms of energy efficiency, end-to-end latency, data delivery ratio and network lifetime.

For the time-sensitive applications, a rendezvous based routing (RRP) with mobile sink is designed. Each sensor node can communicate with the rendezvous region. In RRP, two methods for data transmission are proposed. In the first method, source node directly transmits their sensory data to the rendezvous area. In the second method, the source node retrieves the sink's current position and sends the data to the sink through intermediate nodes. The end-to-end latency and data delivery ratio are improved in the first proposed method. Whereas, the energy consumption and lifetime in the second proposed method are enhanced.

Contents

List of Acronyms

WSN	Wireless Sensor Network
MANET	Mobile Ad hoc Network
SOSUS	Sound Surveillance System
DARPA	Defense Advanced Research Project Agency
ARPANET	Advanced Research Projects Agency Network
DSN	Distributed Sensor Network
RSSI	Received Signal Strength Indicator
LBDD	Line-Based Data Dissemination
MPR	Multi-Point Relay
ART	Adaptive Reversal Tree
GPS	Global Positioning System
FDCM	Fault Diagnosis-based Clustering and Multipath
PPCMP	Practical Passive Cluster based Multipath Protocol
MRP	Multipath Routing Protocol
CMRP	Cluster based Multipath Routing Protocol
TEDD	Tree based Energy-efficient Data Dissemination
CTRP	Clustered Tree based Routing Protocol
RBRP	Rendezvous Based Routing Protocol
EXT	Expected Transmission Count
LIEMRO	Low Interference Energy-efficient Multipath Routing
HEED	Hybrid Energy Efficient Distributed
LEACH	Low-Energy Adaptive Clustering Hierarchy
CH	Cluster Head
MRP	Multipath Routing Protocol
TMAC	Timeout Media Access Control

List of Notations

n	Number of sensor nodes
Vn	Set of sensor nodes
(x_i, y_i)	Location information of node i
d	Distance in meter
d_0	Threshold value of the distance
δ	Pause time of the mobile sink
S_g	Size of the grid
G_x	grid coordinate of any node x
Er	Residual energy of a sensor node
$E_{threshold}$	Threshold energy of a sensor node
$E_{TX}(k, d)$	Transmitting cost of k bits over d meters
$E_{RX}(k)$	Receiving cost of k bits
E_{elec}	The energy consumption of amplifier to transmit or receive one bit
E_{proc}	The processing cost of one-bit of data
ε_{fs}	The energy cost of the amplifier to transmit one bit at one-hop
γ	Path-loss-exponent
ε_{mp}	The energy cost of the amplifier to transmit one bit at multi-hop
E_{low}	The energy consumption of sensor node in sleep mode at one second
$LF(i)$	Location factor of any node i
$Nbr(i)$	One-hop neighbor set of any node i
id_i	Identity information of node i
$NbrTable(i)$	One-hop neighbor information set of any node i

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Chapter 1

Introduction

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Chapter 1

Introduction

Nowadays, the research in Wireless Sensor Network (WSN) is growing due to the advancement of embedded system and wireless technology [1]. WSN has numerous applications in our environment, community, locality, workplace, home and beyond [2]. It is providing new origins of ideas, comfort and ease in the personal and professional life.

The development of WSN started in the 1950s when US military developed the Sound Surveillance System (SOSUS) used in submerged acoustic sensors [3]. For seismic activity surveillance, some of the sensors of SOSUS are still in use. After a gap of nearly three decades the Defense Advanced Research Project Agency (DARPA) in USA started the Distributed Sensor Network (DSN) program that focused on further developments on newly invented technologies and protocols in context of their use for sensor networks [4]. Simultaneously, Advanced Research Projects Agency Network (ARPANET) started research and development in the WSN by involving many institutions and industries [5]. The research and development on small sensor nodes were initiated by NASA 'Sensor web project' and 'Smart dust project' in the year 1998 [6]. One of the objectives of the above project was to create autonomous sensing and communication device within a cubic millimeter of space. Other early projects in this area started around 1999 was primarily in academia at several places, including MIT, Berkeley and University of Southern California [7].

Wireless Sensor Network contains hundreds of thousands of low-cost sensor nodes. A sensor node has constraints like storage, energy, limited processing and transmitting capability [8]. The sensor node monitors the physical and environmental condition, such as temperature, pressure, motion, fire, humidity and many more. WSN is applicable for tracking, surveillance, monitoring, healthcare, disaster relief, event detection, biodiversity mapping, intelligent building, facility management, preventive maintenance, etc. Generally, sensor nodes are deployed in an unattended and hostile environment for monitoring wild forest, battlefield, chemical plants, nuclear reactors and so on [9]. So it becomes a strenuous task to replace or recharge the battery. The sensor node senses not only the environment but also forwards the data to the base station (sink). A base station is a resource-rich device having unlimited power, communication and storage capability. It may be a static node or a mobile node based on the applications and scenarios. It can communicate with the sensor nodes, to collect the data and sends to the user via existing communication system or the Internet. The research have conducted on the data collection among sensors, processing and routing the data during recent years [10–17]. As the sensor network operates in an energy constraint environment, the network often requires an energy-efficient routing protocol to enhance the lifetime of the network.

1.1 Routing in Wireless Sensor Network

Routing technique plays a vital role in the wireless sensor network. It is extremely difficult to assign the global *ids* for a large umber of deployed sensor nodes. Thus, traditional protocols may not be applicable for WSN. Unlike conventional wireless communication networks (MANET, cellular network, etc.), WSN has inherent characteristics. It is highly dynamic network and specific to the application, and additionally it has limited energy, storage, and processing capability. These characteristics make it a very challenging task to develop a routing protocol [18–20]. In most of the scenarios, multiple sources are required to send their data to a particular base station. The nodes near to the sink, depleted more energy and hence eventually die. This causes partitioning of the network; consequently, the lifetime of the network gets to reduce. The main constraint of the sensor node is energy [21,22]. The sensors are battery-powered computing devices. It's hard to replace the batteries in many applications. Therefore, WSN requires an energy-efficient routing protocol. Due to dense deployment, the sensor nodes generate the redundant data, and the base station may receive multiple copies of the same data. Therefore, it unnecessarily consumes the energy of the sensor nodes. WSN does not have any fixed infrastructure and is highly dynamic [23]. There are mainly two reasons responsible for the dynamic infrastructure. The first reason is the energy; the sensor nodes have limited energy in the form of batteries. If the protocol is unable to balance the load among the nodes, the sensor node could die. It leads to the dynamic network structure. The second reason is the mobility; in many scenarios after the deployment, sensor nodes are static but sink can move within the network. It makes the network dynamic, and the protocol that works for static sink may not be applicable for mobile sink [24]. In many applications, sensor nodes are required to know their location information. It is not feasible to enable all nodes with Global Positioning System (GPS) [25]. So the protocol should have to take the help of the techniques like triangulation based positioning [26], GPS-free solutions [27], etc. to get the approximate location information.

1.2 Literature Review

Various researchers have contributed in the area of the routing protocol in wireless sensor networks. Technique reported for routing protocol may be broadly categorized into two groups:

1. Routing protocol with static sink.

2. Routing protocol with mobile sink.

1.2.1 Routing protocol with static sink

The routing protocol with static sink can be classified into *hierarchical-based*, *multipath-based*, *location-based* and *hybrid routing*. In the hierarchical structure, the network nodes are divided into two categories; one work for data collection and sending it to the base station and other sense the environment. The objective of the multipath routing is to provide reliability to the network through available paths between a sensor and the sink. In the location based routing sink knows the location of the source node. Sink sends the query to an interested location to get the data. The combination of two or more above routing protocols can be known as the hybrid routing protocol.

- **Hierarchical-based Routing** In the hierarchical architecture, some higher-energy nodes can be used to process and send the information to the base station while lower energy nodes can perform the sensing in the target area. In other words, the network is partitioned into many clusters. In each cluster, a node is selected as a cluster head with some cluster members. A two-tier hierarchy is formed where cluster heads are in the higher tier while cluster members are created a lower tier. Cluster members sense the data from the physical environment and send it to their respective cluster heads. Cluster heads process the data and transmit it to the sink either directly or in the multi-hop manner.

  Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol has been proposed by Heinzelman *et al.* [28]. It is the first hierarchical clustering approach in WSN. In the LEACH protocol, the operation consists of many rounds. Each round has two phases; the set-up phase and steady-state phase. In the setup phase, the cluster is formed and in the steady-state phase, data is transmitted to the base station. The cluster head are elected based on the predefined percentage of cluster heads and how many times the node has been a cluster head in previous rounds. LEACH can balance the load among the cluster heads up to some extent. Individual time slot prevents cluster head from unnecessary collisions and avoids excessive energy dissipation. On the contrary, LEACH is not applicable to large-area networks, and uneven distribution of cluster head brings extra overhead.

  Younis and Fahmy have proposed a Hybrid Energy Efficient Distributed clustering (HEED) routing protocol [29]. It is a multi-hop clustering algorithm for wireless sensor networks, which focus on efficient clustering by proper selection of cluster heads. The cluster head is selected based on criteria such as residual energy and intra-cluster communication cost. HEED is a fully distributed clustering method and provides uniform CH distribution across the network. The communications are in a multi-hop fashion between CHs and the base station. However, it generates more CHs than the expected number, which decreases the network lifetime.

Power efficient gathering in sensor information systems has been proposed by Lindsey *et al.* [30]. It is an improvement over LEACH protocol. This protocol requires the formation of a chain that is achieved in two steps: chain construction and gathering data. The basic idea of the protocol is that the nodes need to transmit only with their closest neighbors, and they take turns in communicating with the base station. It reduces the overhead of dynamic formation of clusters, and through the chain method, it decreases the data transmission. The energy load is dispersed uniformly in the network. In contrast, the delay is increased for the distant nodes due to a single chain and can reduce the performance.

Huan Li *et al.* [31] have proposed an approach for constructing optimal clustering architecture. The node with high residual energy claims as the new cluster head. Then the cluster head collects all the data from their neighboring nodes and sends it to the sink. It selects the cluster head who has highest residual energy. It obtained an optimum number of clusters to cover a sensing area to minimize the energy consumption per cluster. Also the variance of energy consumption among the clusters. Although it is a distributed protocol and works well with a large number of sensor nodes, it consumes a large amount of energy in obtaining residual energy information of the neighbor nodes.

Ouadoudi Zytoune *et al.* [32] have proposed an energy aware clustering technique, where the network is divided into clusters. A cluster head is selected to monitor and control the cluster. The cluster head can directly transmit the data to the base station. The cluster heads are elected based on the ratio of residual energy and the average energy of the network. This protocol provides a stable network. It reduces the number of control message, so the lifetime increases. On the other hand, it is only suitable for heterogeneous network and work for limited applications.

A clustering technique called the limiting member node clustering proposed by W. Naruephiphat *et al.* [33]. This algorithm considers a maximum number of member nodes for each cluster head. It divides sensor nodes into groups where nodes within the transmission range of base station are defined in level 1 and nodes far from the base station are defined in a higher levels depending on the distance from the base station. In this approach, each sensor node selects a cluster head from the candidate list of cluster heads based on a cost function that considers energy consumption, battery level and distance from the base station. This protocol will limit the number of member nodes of each cluster head to be less than a threshold value in order to distribute the burden of each cluster head. It prolongs the network lifetime and reduces the time to forward the data packet to the base station.

Chang and Ju [34] have proposed a save energy clustering algorithm. In this algorithm, the cluster head election process includes location, the average residual energy of the sensor nodes and residual energy for each sensor node. The sensor node becomes a candidate cluster head when the residual energy of the node is greater than the average residual energy of the sensor nodes. The load balancing among the clusters can prolong the lifetime of the network. It consumes low energy that extend the network lifetime. However, it is a centralized algorithm and required the location information of each node.

A centralized energy-efficient routing protocol called LEACH-C has been proposed by Muruganthan *et al.* [35]. LEACH-C is a modified LEACH using centralized clustering control. In the setup phase, the base station collects the location information and residual energy of each node in the network and based on this base station selects the cluster heads and configures the rest of the nodes into clusters. Both intra-cluster communication and inter-cluster communication are single-hop communication. Since the base station has the knowledge of the network and information of energy and location of sensor nodes, it creates better clusters that require less energy for transmitting data. In contrast, it causes extra overhead on providing the information to the base station and is not applicable for large networks.

- **Multipath-based Routing** Multipath routing is an alternative routing technique, which selects multiple paths to deliver data from source to destination. It allows multiple paths between the source and the sink. Due to the use of redundant paths, multipath routing can largely address the reliability and load balancing issues. Many multipath routing protocols have been proposed for WSNs. The existing protocols on multipath routing tried to cope with load balancing and resource limitations of the low-power sensor nodes through concurrent data forwarding over multiple paths.

  Directed Diffusion routing protocol has been proposed by Intanagonwiwat *et al.* [36]. It is a query based multipath routing protocol, where the sink initializes the routing process. The sink floods the interest into the network. During the interest message flooding all the intermediate nodes store the interest message received from the neighbors for later use and creates a gradient towards the sender node. During this stage, multiple paths can be discovered between each source-sink pair. Then the source transmits the data through the selected path. Further the sink continues to send low-rate interest message over the remaining paths, this is done to preserve the freshness of the interest tables of the intermediate nodes, and also maintain the discovered routes. If the active path fails, the data can be forwarded through the other available paths. Although, it provides fault-tolerant routing, it evolves all the nodes in route discovery. As a result, it affects the network lifetime.

  Ganesan *et al.* [37] have proposed a braided multipath routing protocol, which constructs multiple partially disjoint paths. It provides fault tolerance in the sensor network. This protocol establishes routes using two path reinforcement messages. One is the primary path, and another is the alternate path reinforcement message. The sink initializes the path construction by sending a primary path reinforcement message to the best next-hop neighbor towards the source node. This process continues until the primary reinforcement message reaches the source node. The primary node also sends the alternative path reinforcement message to the next-best neighbor towards the node of origin.

This process results in the construction of backup paths. Whenever the primary path fails, data can be forwarded through the alternate path.

Ye Ming Lu *et al.* [38] have proposed a distributed, scalable and localized routing algorithm . It discovers multiple node-disjoint paths between the sink and the source nodes. It also uses a load balancing algorithm that distributes the traffic over the multiple paths. When an event is detected, it selects a node from the event area as the source node. The source node then starts the route discovery process. The sink sends multiple route request messages to its neighboring nodes with distinct path *id* to build node-disjoint paths. After receiving the first route request message from the source node, the sink starts a timer. Any path discovered after the timer stops are discarded. The sink also optimally assigns the data rate for each path.

M. Maimour [39] has proposed a Maximally Radio-disjoint multipath routing (MR2), which deals with the interfering paths. Its main objective is to provide the necessary bandwidth to multimedia data through non-interfering paths. It constructs the minimum interfering paths using the adaptive incremental method. Only one path is built at a time, and additional paths are constructed when required, typically in case of network congestion or bandwidth shortage. The protocol reduces the effects of interference by keeping some sensor nodes in the sleep state. After going to sleep state, the sensors will not take part in any routing process. However, MR2 is only suited for the query based applications and used flooding technique to construct non-interfering paths.

Wang *et al.* [40] have proposed an energy-efficient and collision-aware multipath routing protocol. It is a reactive routing protocol. It creates two collision-free paths between the source and the sink using the location information of all the sensor nodes. In this protocol, each node sends a route discovery message with proper power and node position information. It is assumed that all nodes have a transmission range of 0 to R, and all nodes know their neighbor information within that range R. Hence to decrease the chance of interference, all routing paths are built above this range. The broadcasting is used to detect collision, and the nodes that are overhearing from other routes cannot be in any route. However, the cost of the network deployment is more due to the GPS device requirements for each node within the network.

Low Interference Energy-efficient Multipath ROuting (LIEMRO) has been proposed by Radi *et al.* [41]. It improves the latency, lifetime and packet delivery ratio by applying node-disjoint paths. It includes a load balancing algorithm to distribute the source node traffic over multiple paths based on the relative quality of each path. It also calculates the cost of the link, which is done by the Expected Transmission Count (ETX) [42] metric. In this method, the sink sets its cost to zero and broadcast a control packet to its neighbors. Each neighbor then calculates its link cost with respect to the sink. Further, they broadcast the information in the network until the source node receives the information. The route discovery phase is initialized, as soon as an event is detected in the network. The source sends the route request to the sink to start the route establishment. The path with lesser residual energy transmits the data with a lower rate to save the energy. LIEMRO maintains the traffic rate dynamically based on the quality of the paths. However, it does not consider the service rate and the buffer capacity of the active nodes to adjust and predict the traffic rate of the active paths.

Cherian *et al.* [43] presents a novel multipath routing algorithm that increases the reliability by using multiple paths and scheduling data transmission rates at each node. This approach helps to prevent congestion and packet loss. Each node in the network maintains two queues for incoming data and three queues for transmitting the data. Also, every packet is assigned a priority number based on its information. All the nodes in the network act as a scheduling unit and whenever any node receives the data packet, they put the packet in the appropriate queue. Later on, the node will select the packet based on the priority number from the queue and schedule a transmission to its next available multiple nodes. By using this approach the traffic on the network, is controlled by adjusting the queue length. It provides a high rate of reliability in the presence of channel errors. However, it does not provide a way to detect the failed nodes.

- **Location-based Routing** In the location-based routing, sensor nodes are known by their locations. The node can find the distance to the neighbor based on the received signal strength. The relative coordinates location information can be calculated by exchanging the control packets between the neighbor nodes. Alternatively, each node has to use the Global Positioning System (GPS) [25]. The unknown nodes can calculate approximate location information by referring the position of the known nodes.

  Greedy perimeter stateless routing has been proposed by Karp and Kung [44]. It makes the data packet forwarding decisions using nodes location information. It uses greedy forwarding and perimeter forwarding techniques to forward data packets to the nodes that are always closer to the target node. In regions of the network where such a greedy path does not exist, the protocol recovers by forwarding in perimeter mode. The position of a packet's destination and positions of the next hop neighbor are sufficient to make correct forwarding decisions, without any other topological information.

Y. Xu *et al.* [45] have proposed a geographic adaptive fidelity routing. In this approach, the network is partitioned into equal sized virtual grids. Inside each grid, nodes will elect one sensor node as a leader to stay awake for some duration and other nodes can switch to sleep mode. This node monitors and reports the event to the base station on behalf of the other nodes in the grid. Thus, the network conserves energy without affecting the routing accuracy. Each node has three defined states: discovery, active and sleep. However, the leader node does not do perform any aggregation as hierarchical protocols discussed earlier.

Zhang *et al.* [46] have proposed an Energy-efficient geographic routing. It considers both nodes location information and energy consumption for making routing decisions. Instead of forwarding the data packets to the neighbor closest to the sink or neighbor has maximum residual energy, the packet are transmitted to the neighbor that is closer to the energy optimal relay position. In this protocol, all nodes are not required to maintain neighbor information. The optimal relay node is computed by broadcasting small control packets having the location and residual energy information. It is fully localized, stateless and energy-efficient protocol. It only works well in the uniformly deployed network.

Alasem *et al.* [47] have proposed location-based energy aware and reliable routing, which is based on sensor position. The location information that has been used in the protocol could be extracted from GPS. Each node sends its location information to its neighbors and constructs a routing table. The routing table consists of neighbor node *id* and the distance from the destination node. The routing decision is taken by the source using the distance. The node with the shortest distance is selected as the candidate relay node to send the information.

A reactive geographic routing protocol has been proposed by Ding *et al.* [48]. It combines reactive routing mechanism and geographic routing. It is calculating the shortest distance between destination node and neighbor node. The protocol uses two new measures to improve the performance of routing protocol. First, to reduce the consumption, it uses reactive routing mechanism to mitigate the routing overhead. Second, to improve reliability, it finds the optimal path from the many available paths.

Energy-efficient geographic routing algorithm has been proposed by Chen *et al.* [49]. It considers three factors for the routing decision such as routing distance, signal interference, and computation cost. In the protocol, two methods for the routing decision have been proposed. In the first method, it takes the decision based on the distance and signal interference. It finds the Euclidean distance from the transmitter node to the destination node and interference power. In the second method, it takes the decision based on the maximum power consumption and interference power.

- **Hybrid Routing** The hybrid routing is a combination of any of the above routing protocols. It takes the benefits of more than one protocols to enhance the performance of the network. Many researches have been done using the hybrid approach in the routing protocol for wireless sensor network.

  Bagheri *et al.* [50] have proposed reliable and energy efficient clustering based multipath routing protocol, where nodes are enabled with the GPS. The cluster head section is based on the remaining energy of the node. The sink initiated the route discovery by sending a request packet to its nearby cluster heads, and request reaches the source cluster head. The source cluster head may receives more than one requests. The multipath routes are constructed through the cluster heads. A cluster head selects another path if existing path fails.

  An event-based multipath clustering protocol has been proposed by Quynh *et al.* [51]. When an event is detected, all nodes near the event will active. One of the nodes close to the event having maximum residual energy is elected itself as the cluster head. The rest of the active nodes join the cluster head and form the cluster. The cluster head chooses the relay node and backup relay node towards the sink to form the multipath. When the link fails, the protocol selects the backup relay node for data transmission.

Mazaheri *et al.* [52] have proposed a QoS base energy aware multipath hierarchical routing. It elects the cluster head in the range r based on the remaining energy and the distance from the sink. For multipath construction, cluster head chooses a set of cluster heads within the range R (where, $R > r$) based on the residual energy, remaining buffer size, signal to noise ratio and distance to the sink. It distributes the load among the relay paths to send the data, which reduces the end-to-end latency.

A Practical Passive Cluster based Multipath Protocol (PPCMP) has been proposed by Jin *et al.* [53]. In this protocol, the node near to the event becomes the candidate cluster head and waits for a certain time. If it does not receive any cluster head advertisement within that time, it becomes the cluster head and broadcasts the advertisement in its range (R). The node resides within $\frac{R}{2}$ range joins the cluster and rest of the nodes up to the range R become the candidate cluster head and follow the same procedure for cluster formation. Branch aware flooding method [54] is used to construct the multipath between the sink and the source node. For the next time if any source detected the event, the same available set of clusters are used, but a new set of multipath is required for data transmission. In the protocols [50–53] the control packet overhead is more, which leads to the higher energy consumption. It directly affects the lifetime of the network. These protocols give more emphasis on reliability through the multipath but neglect some QoS parameters such as end-to-end delay, control overhead and network lifetime.

A cross-layer based clustered multipath routing has been proposed by Almalkawi *et al.* [55]. The nodes are heterogeneous and randomly deployed. The sink initiated the cluster formation by broadcasting the control packet. Based on the received signal strength the powerful nodes become the cluster heads. The cluster heads are classified in different levels. They send the data through the upper-level cluster head.

A Fault Diagnosis based Clustering and Multipath routing (FDCM) has been proposed by W. Liu [15]. For cluster formation, base station randomly chooses a particular number of candidate cluster heads on certain probability. The candidate cluster head checks the fault status of each other. Once the faulty node is detected, it is removed from the network. Among the neighbor candidate cluster head having the highest residual energy becomes the cluster head and the non-cluster head nodes join the closest cluster head and form the cluster. For multipath construction, a cluster head chooses the cluster head within the $2R$ range having the smallest distance from the sink. The protocols [15, 55, 56] do not maintain the proper path. They only have the information regarding neighbor nodes. They have to choose a node from the neighbor list without knowing their current residual energy or connectivity with the other nodes. It decreases the reliability of the networks.

Wang *et al.* [57] have proposed a hierarchical multipath routing protocol. Each node has a hop count value that indicates the distance to the sink. Based on the hop count the node selects the parent and alternate parent node to make the multipath. The network looks like a tree with the sink as the root node. Using hierarchical structure, it reduces some amount of data traffic and energy consumption.

Yang *et al.* [58] have proposed an event based routing protocol. The node closest to the event becomes the cluster head and the node that satisfies certain threshold joins the cluster head. The ant colony algorithm [59] was used to create multipath between the cluster head and the sink. The cluster head dynamically chooses the routing path between the available path to send the aggregated data to the sink. The protocols [15, 52, 55, 57, 58] have not used any load balancing technique among the nodes. It leads to the mismanagement of the network and reduces the throughput and network lifetime.

1.2.2 Routing protocol with mobile sink

In the routing protocol with static sink, the sensor nodes close the sink always forward a large amount of data; as a result they die. Finally, the network is partitioned, and the sink can not receive any data. This phenomena is known as crowded center effect [60] or energy hole problem [61]. A mobile sink is used in the network to overcome this problem. The mobile sink makes the network dynamic, and routing becomes difficult. In this section, a study on the existing routing protocols with mobile sink is done. They are categorized and explained. The routing protocol with mobile sink can be classified into *hierarchical-based*, *tree-based* and *virtual-structure-based*.

- **Hierarchical-based Routing** In hierarchical routing protocols, the entire network is broken into layers. The higher layer nodes are assigned some specific tasks like processing and sending the information while the lower layer nodes are used for sensing in the proximity of the target. Data travels from the lower layer nodes to the higher layer nodes while the queries go from, the higher layer nodes to the lower layer nodes. In the hierarchical approach, a virtual hierarchy of nodes is created in the network that imposes different dynamic roles on the sensors. The hierarchy might be composed of two or more tiers. A successful hierarchical approach must employ easily accessible structure and should avoid energy hole problem [61] on the higher tier nodes.

  Lin *et al.* [62] have proposed a hierarchical cluster-based data dissemination protocol. It uses a clustering structure to track the location of the mobile sinks and finds the paths from the source to the sink for data transmission. Each cluster consists of a cluster head, several gateway nodes, and ordinary nodes. The mobile sink registers itself to the nearest cluster head, and a notification is then disseminated to all the cluster heads. In this process, each cluster head makes a reverse link to the sender node for transmitting the data.

  A mobile routing algorithm in cluster-based architecture has been proposed by Wang *et al.* [63]. Each sensor node finds the neighbor information like its residual energy and location by broadcasting a small control packet. The cluster heads are elected based on the higher residual energy among the neighbors. The cluster head broadcasts the advertisement to create a cluster. The cluster members join the cluster head and form a cluster. The mobile sink moves within the network using the random waypoint mobility model. The sink broadcasts the location information when it reaches to the new location. The cluster heads create the routing path based on the location information and send the aggregated data to the sink.

A mobile-sink based energy-efficient clustering algorithm has been proposed by Wang Yin *et al.* [64]. In this approach, the cluster head is selected based on the residual energy. The cluster head aggregates the data and transmits it to the mobile sink. The mobile sink sends their location information just for once. The sink follows the paths that are easily predictable by the sensor nodes. The sensor nodes keep track of the current position of the sink by calculating it using the initial location of the sink. However, this protocol performs well in the predictable mobility model environment.

Wang *et al.* [65] have proposed an energy-aware data aggregation scheme. It is a hierarchical hybrid routing protocol that comprises of on-demand data dissemination tree with grid structure. Sensor nodes enabled with Global Positioning System (GPS). A gateway node is selected with highest residual energy around the sink. Gateway node is responsible for aggregating data, forwarding the sink queries towards the interest zone and transferring the source generated data to sink. It is changed periodically according to sink movement. Energy consumption of this protocol is less when maximum sink speed is considered. It performs in-route data aggregation, which increase the energy efficiency.

- **Tree-based Routing** The management of sink mobility is very importance in the mobile sink environment. The tree-based routing is the efficient solution to that problem. Through the connected structure like a tree, it is very easy to manage the sink mobility. In the tree structure, any source node can send their data to the sink with minimal cost.

Kim *et al.* [66] have proposed scalable energy-efficient asynchronous dissemination protocol. It constructs a tree to disseminate the data to the sink through an access node. It is the sensor node that send the data directly to the sink and location of the sink known to the access node. Sink elects an access node when it reaches a new location. The dissemination tree is reconstructed in the case where the sink elects the new access node. In this protocol, a trade-off exists between minimizing the delay and saving the energy spent on reconfiguring the tree. The sink can move without reporting their location to the tree. The concept of the access node is well defined for the real-time applications. However, The tree construction is required when sink elects the new access node, which increases the overall cost.

Adaptive Reversal Tree (ART) protocol has been proposed by Hwang *et al.* [67]. Here, a tree with a temporary root is constructed, and all paths are directed toward the root. The root node is linked with the sink. The source node sends their data to the sink through this tree. The sink selects a new neighbor node as the root node. The new root node reconfigures the affected area. The tree structure changes based on the new position of the sink. The efficiency path-repair method reduces the communication overhead, but the routing paths are sub-optimal, which increases the latency.

Wang *et al.* [68] have proposed a local update-based routing protocol. The basic idea behind this protocol is to restrict the scope of the frequent location updates for a mobile sink to a local area called a destination area, and hence reduce communication overhead. In this protocol, a mobile sink defines a circular destination area by selecting its current position as a virtual center and an updated range of L. The location of the virtual center and the selected update range are then flooded across the entire network. When the mobile sink moves inside its destination area, it only broadcasts the location information to the nodes inside its destination area. The data forwarding process has two stages. Outside the destination area, data packets are forwarded toward the virtual center via geographical forwarding. Inside the destination area, topology-based routing is used. Once the sink moves outside its current destination area, it needs to redefine a new destination area and flood its new virtual center information across the entire network.

Hwang *et al.* [69] have proposed a distributed dynamic shared tree protocol, which supports the multiple sinks. In the protocol, the root of the tree is the sink and based on the new position of the sink the tree is created. In this protocol, one master sink, and many slave sinks collect the data. The root of the tree is the master sink and slave sinks are connected with the master sink. The data are received through the path from the source to the master sink and from the master sink to the slave sinks.

A flexible probabilistic data dissemination protocol called SUPPLE has been proposed by Viana *et al.* [70]. The SUPPLE protocol creates a tree structure initiated by a central sensor node of the sensing region. This sensor node is responsible for receiving the data and replicating the collected data. The data is replicated to the storing nodes in the networks. The storing nodes are selected by the central node using the weight based on the storage probability. The mobile sink collects the data from the storing node when it reaches in its territory. The communication overhead is less for maintaining the sink mobility. However, SUPPLE suffered from control packet overhead and increased end-to-end latency.

A Multi-Point Relay based routing protocol called SN-MPR has been proposed by Yasir *et al.* [71]. SN-MPR is based on the Multi-Point Relay (MPR) algorithm [72]. The sensor nodes in the network are divided into two categories, the MPR node, and non-MPR. The MPR nodes are selected based on their residual energy. The sink broadcast its location update to the neighbor nodes. Only MPR nodes are allowed to forward the sink's location update to the network. The node receives the sink's location update makes a reverse link towards the sender node. As a result, the path towards the sink is created for each sensor nodes. When the sink moves to the new location, it broadcast again the sink's location update to construct the path. In SN-MPR, the root of the tree is the sink. Hence, the sink movement affects the tree structure that causes energy consumption.

- **Virtual-structure-based Routing** A virtual infrastructure over the network has often been investigated as an efficient strategy for data dissemination in the presence of mobile sinks. The concept of virtual infrastructure acts as a rendezvous area for storing and retrieving the collected data. The sensor nodes belonging to the rendezvous area are designated to store the generated measurements during the absence of the sink. Once, the mobile sink crosses the network, and the selected nodes are queried to report the sensory input. This virtual infrastructure can be built using a backbone based or a rendezvous-based approach.

  Luo *et al.* [73] have proposed a two-tier data dissemination protocol. It supports multiple sinks and adopts a grid infrastructure. In the protocol, when a source node detects any event, it builds a virtual grid. The dissemination nodes are selected based on the distance from the grid's crossing points. These dissemination nodes transmit the data about the deleted event and the source node *id*. The mobile sink broadcasts a query when it requires the information. The dissemination node in its proximity forwards the sink query towards the source through the virtual grid. The source node transmits the information to the sink on the reverse path. The protocol needs different routing path for different event detecting nodes. The overhead of the network is more when the number of event increases.

  Grid-based energy-efficient routing protocol has been proposed by Kweon *et al.* [74]. Unlike the two-tier data dissemination protocol, in this protocol a permanent grid structure are built based on the location aware nodes after the deployment. The grid is partitioned into cells. A head node is selected randomly in each cell. Data packets and data queries are transmitted between the sensor nodes and the sink through the header nodes. Greedy geographical forwarding mechanism [44] is used to propagate the data. Sink query and sensory data are transmitted along a straight line path. However, this mechanism is not suitable for applications where the environment is hostile. The average delivery ratio decreases as the number of sink or the source node increases.

Hamida *et al.* [75] have proposed a Line-Based Data Dissemination protocol (LBDD). It defines a virtual horizontally centered line, which divides the sensor field into two equal parts. This line is also divided into groups. This line acts as a rendezvous region for data storage and looks up. This virtual line is placed in the center of the field to make it accessible by each node. The nodes within the virtual line are called inline-nodes, and the rest of the nodes rare called ordinary nodes. When an ordinary node generates a new data, it transmits the data towards the virtual line. The inline-node stores the data and waits for the sink query. The sink transmits a query towards the virtual line in the horizontal direction. The inline-node that receives the query disseminates it in both the directions in the virtual line. When the storing inline-node receives the query, it directly sends the data to the sink.

Shin *et al.* [76] have proposed Railroad protocol, which constructs a virtual structure called the rail that is placed in the middle area of the network. It is a closed loop of a strip of nodes, shaped to reflect the outline of the network. The nodes inside the rail are called rail-nodes. At the center of the rail, the stations are construed by rail-nodes. When a source node generated the data, it sends information about the data called meta-data to the nearest rail node. This message travels within the rail until it reaches the rail-nodes that store the relevant source node information. The meta-data is shared among the nodes on the station. The sink queries the rail for meta-data, and when the query is reached a station node, it informs the source about the sinks position, and data is forwarded directly to the sink. In Railroad, the sink's queries travel on the rail by unicast rather than broadcasts.

An energy-efficient routing protocol called Ring Routing has been proposed by Tunca *et al.* [77]. It establishes a ring structure that aims to combine the easy accessibility of the grid structures and the easy changeability of the backbone structure. Since it incorporates a minimal number of nodes in the ring structure, the redundancy of data packets is significantly reduced for sharing sink position advertisement packets among the ring nodes. It devises a straightforward and efficient mechanism. The ring can be constructed with low overhead unlike the structures utilized in the area-based approaches as in LBDD and Railroad. On the other hand, Ring routing relies on the minimum amount of inefficient broadcasts which are extensively used in area-based protocols.

1.3 Issues and Challenges for Routing in Wireless Sensor Networks

In the highly dynamic and energy constraint network, it is a challenging task to develop a routing protocol. The design of the routing protocol can be affected by many characteristics possessed by the WSN. A few issues and challenges for routing in WSN are discussed below:

- **Energy constraint:** The sensor nodes are battery-powered devices, hence have limited energy. A large amount of energy is consumed during data transmission. Furthermore, a significant amount of energy is consumed during the route discovery and its maintenance phase. The lifetime of the network directly depends on the total energy consumption by each node [78]. If a sensor node's energy reaches below a certain level, it will become nonfunctional and affects the performance of the network. Therefore, it is a big challenge for a routing protocol designer to manage the energy of the sensor nodes to maximize the network lifetime.

- **Bandwidth constraint:** Generally, WSN consists of a large number of sensor nodes, which makes the bandwidth allocation for each link very challenging. Moreover, in the process of route discovery and maintenance, an enormous amount of control packets has to be broadcasted among the sensor nodes. Thus, the network bandwidth allocation process depends on the number of links and the amount of data they can communicate [79].

- **Limited hardware constraint:** Sensor nodes are tiny embedded devices having limited processing and storage capacity. Therefore, the researchers have to design a light-weight routing protocol that does not have complicated computing procedures and functions. Hence, the sensor nodes can process and store the data efficiently [22].

- **Crowded center effect:** The data communication from source nodes to a sink in WSN is the many-to-one relationship. In the multi-hop environment, each sensor node forwards the data to the sink through intermediate sensor nodes. The sensor nodes near the sink always relay a large number of data. Therefore, they consume more energy than the remaining nodes and finally die. This issue is named as crowded center effect [60] or energy hole problem [61]. This leads to a partitioning between the sink and the source node in the network.

- **Node deployment:** The sensor node deployment entirely depends upon the applications. In some applications, structured deployment is required whereas, in some scenarios, random deployment is needed. In the random deployment, the node location is not predefined and generally, thrown from an aircraft in the hostile or unattended area. The node deployment highly affects the network performance [7].

- **Mobile node information:** After the sensor node deployment generally, the nodes are static. However, in some applications, the nodes are mobile. There should be a proper way to locate those mobile nodes to communicate with the static node. In some applications, the sink is moving within the network for data collection. So the routing protocol should be able to inform the sink location to the nodes within the network [80].

- **Sensor node location:** The geographical location information of the sensor nodes is required in many applications like tracking, monitoring, event detection, etc. It is not possible to enable the GPS in every single node [25]. Instead; unknown nodes can find the location using the methods like triangulation based positioning and GPS-free solutions. The routing protocol should be able to locate the sensor nodes using the location finding techniques [26, 27].

- **Scalability:** A large number of sensors are deployed in the interested area. Further, during the operation, the network size may increase. The protocol has to be designed in such a way that the node scalability does not affect the performance [9].

In addition to the above challenges, two significant aspects of WSN have to be addressed such as energy constraint and mobile node information. The detail about energy management and mobile sink management and the necessary factors that need to consider are described below.

1.3.1 Energy Management

The routing protocol can use some techniques to improve the energy-efficiency and network lifetime. A few techniques of energy management are discussed below:

- **Energy model:** The energy model of the sensor node in any routing protocol can help to improve the network performance [81]. The accurately defined energy model can give a better estimation of remaining energy in each node. It makes monitoring simple and straight. The model with detailed view and correct approach can improve the network lifetime.

- **Minimize the collision:** In routing protocol, the data should reach the base station without any interference [79]. The protocol has to make sure that each node should communicate in the congestion-free environment. Otherwise, it may lead to re-transmission of data, which directly affect the energy-efficiency of the network.

- **Minimize the control packet overhead:** In signal transmission, the sensor node consumes the maximum amount of energy [82]. In routing protocol for neighbor information; route discovery and maintenance involve plenty of control packets exchanged between sensor nodes. The routing protocol needs to restrict the unnecessary flow of control packet in the network. The size of the control packet may also affect the overall energy consumption.

- **Allow multi-hop communication:** The direct data transmission always consumes more energy than multi-hop communication [83]. In direct communication, the sensor node has to maximize the radio transmission power, which directly increases the energy consumption at each node. The routing protocol needs to take care of this issues to improve energy-efficiency.

- **Using the energy-aware MAC protocol:** The sensor node senses the environment, generates the data and forwards it to the sink [5]. When the sensor nodes are not sensing or routing, they need to switch into sleep mode. Therefore, a suitable MAC protocol is required for the energy conservation in the network.

- **Load balancing:** In the distributed environment where each sensor node has to manage itself, the residual energy information plays the vital role [22]. By using the energy model, each node calculates their residual energy. The routing protocol has to manage the load among the sensor nodes in such a way that more works should assign to an energy-rich node and reduce the workload from the nodes having less residual energy. The proper load balancing technique improves the energy-efficiency.

- **Transmission range adjustment:** WSN is a multi-hop network where data should reach the destination through the intermediate nodes. Generally, during deployment it is found that the next available relay nodes are always in close vicinity of the sender node. Hence, instead of sending the data with maximum power the transmission power can be readjusted using the Received Signal Strength Indicator (RSSI) [84]. This technique can reduce the energy consumption and helps to improve the network lifetime [85].

- **Data aggregation:** The similar data packets can be aggregated at some point and can send the aggregated data to the sink [86]. The technique of aggregating similar data decreases the traffic in the network [87]. The reduced traffic decreases the collision and energy consumption. The routing protocol needs to implement the aggregation technique to prolong the lifetime of the network.

1.3.2 Sink Mobility Management

The mobile sink uses reduced path length for data transfer, which limits the latency and improves the network lifetime. The crowded center effect [60] or the energy hole problem [61] can also be solved using the mobile sink. In contrast, the complexity of the routing protocol may increase to manage the mobile sink. Mobility makes the network dynamic in nature. The routing technique used for the static sink will not be applicable for the mobile sink. The sink mobility can be categorized in the following types:

1. **Controlled mobility:** This mobility is based on the predefined schedule [88]. The node chooses the next visit using the previous position and direction. The controlled mobility sometimes helps to improve the lifetime, as it affects only some portion of the network.

2. **Predictable mobility:** The position and time have been defined for the next visit of the sink [89]. So that source node can switch to sleep mode when the sink is not visiting in the territory.

3. **Random mobility:** Unlike the controlled mobility, the random mobility does not depend on the previous location. Instead, it computes the next position and direction arbitrarily [89]. The management of random mobility is very difficult for the sensor node as it affects the large portion of the network. Due to randomness, the sensor nodes are not allowed to switch to sleep mode. As a result, it increases the energy consumption.

Depending on the application, the mobility pattern has to be chosen so that the energy-efficiency can improve. The routing protocol should manage the sink mobility in such a way that the affected area can be reduced, and the control packet flow will be less. Furthermore, the involvement of a small number of sensor nodes in the sink management can improve the energy-efficiency.

1.4 Motivation of the Research

Sensor nodes are driven by the battery and in many applications, these batteries cannot be replaced. They die when the battery exhaust and the network functionality are affected. Thus, a routing technique is very much essential to enhance the life span and manages the battery efficiently. This characteristic motivates to design energy-efficient routing techniques.

Wireless sensor network is a multi-hop network where data are transmitted through the intermediate sensor nodes. The links between sensor nodes are highly prone to failure. The frequency of link failure directly affects the data delivery ratio and decreases the reliability of the network. This issue motivates to design reliable routing techniques.

The energy hole problem can be solved using the mobile sink. However, the mobile sink management is a tedious task. Many routing protocols are working in the mobile sink environment but possess flaws like; ineffective management, increased energy consumption, and reduced data delivery ratio. It is essential to efficiently manage the mobile sink to prolong the lifetime of the network.

In many applications, the generated data should reach the base station at the earliest. However, the unavailability of the routing path, sink location and frequency of node failure increases the end-to-end latency. Therefore, it is required to incorporate techniques to reduce latency.

1.5 Objectives of the Research

To enhance the network lifetime and manage the mobile sink, energy-efficient techniques are required in routing protocol. The objectives of the thesis are listed as follows:

(i) Designing of a multipath routing protocol to enhance the reliability and energy-efficiency.

(ii) Proposing a cluster based multipath routing technique to improve energy-efficiency and reliability.

(iii) Developing a tree-based routing technique in the mobile sink environment.

(iv) Designing of a dense tree based routing technique with mobile sink to efficiently manage the sink mobility.

(v) Developing a clustered tree based routing technique with the mobile sink environment.

(vi) Developing a rendezvous based routing with mobile sink to reduce the latency and increase the network lifetime.

1.6 Organization of the Thesis

The rest of the thesis is organized as follows:

- **Chapter 2: Multipath Routing Protocol with Static Sink**
  This chapter presents the Multipath Routing Protocol (MRP) for energy-efficient and reliable data communication. More than one routing paths are available for data transmission. If one path fails, an alternate path is used to transmit the data. The sensor nodes can go to sleep mode if not involved in the routing path.

- **Chapter 3: Cluster based Multipath Routing Protocol with Static Sink**
  This chapter introduces an energy-efficient Cluster based Multipath Routing Protocol (CMRP). Its features involved: alleviation of workloads (cluster formation, routing path selection and energy management) from the sensor

node and give these works to the base station. That eventually reduces the control packet overhead and increases the lifetime.

- **Chapter 4: Tree based Data Dissemination Protocol with Mobile Sink**

  This chapter presented the novel routing protocol called Tree based Data Dissemination protocol (TEDD) to efficiently manage the sink mobility. At the same time, each node is connected to the network through the tree structure. It is an energy-efficient technique, which can reduce the end-to-end delay and increase the data delivery ratio.

- **Chapter 5: Dense Tree based Routing Protocol with Mobile Sink**

  This chapter is an improvement over TEDD technique. The idea is to reduce the number of relay node to further decrease the number of hop count for data transmission and conserve more energy in the network. Its unique load balancing technique increases the network lifetime.

- **Chapter 6: Clustered Tree based Routing Protocol with Mobile Sink**

  This chapter introduces Clustered Tree based Routing Protocol (CTRP). Its clustering technique reduces the traffic in the network, and tree structure always maintains the connectivity in the network. This method increases the energy-efficiency and reduces the end-to-end latency.

- **Chapter 7: Rendezvous based Routing Protocol with Mobile Sink**

  This chapter presents a unique technique of data transmission to mobile sink called Rendezvous based Routing Protocol (RRP). This protocol creates a cross structure in the network. RRP has two proposed method for data transmission. In the first method, the data is transmitted to the rendezvous region. In the second method, the source node retrieves the sink location from the rendezvous region and sends the data directly to the sink through intermediate nodes.

- **Chapter 8: Conclusions**

  This chapter provides the brief description of the work done. It includes highlighting factors of the contributions and remarks on achievements. The scopes for future research are projected at the end.

The contributions made in each chapter are discussed in the sequel, which includes system model, proposed schemes, their simulation results and analysis.

Chapter 2

Multipath Routing Protocol with Static Sink

Chapter 2

Multipath Routing Protocol with Static Sink

2.1 Introduction

The design of reliable routing protocols is resistant to frequent path disruptions caused by node failure and collision. The routing path should be maintained while data transmission otherwise re-transmission of data increases energy consumption. Some protocols [44, 46–49, 78, 79, 90] discover routing path but often fails while transmission, which decreases the reliability. The data should reach the base station (sink) through a reliable path. The solution to this problem is multipath routing. Multipath routing protocol allows numerous paths between the source and the sink. So if one path fails, data can still be sent through the different available path. This increases the reliability of the system. Due to the dense deployment of sensor nodes, it is possible to construct multiple routing paths [91]. This motivated us to use the concept of multipath routing for reliable data transmission. A number of routing protocols [37–41,92–94] maintain the multipath at the cost of energy consumption.

In this chapter, a Multipath Routing Protocol (MRP) is proposed, which reduces the control overhead for route discovery and increases the throughput of the network. The proposed multipath routing protocol is designed to improve the lifetime, latency and reliability through discovering multiple paths from the source node to the sink. MRP is the sink initiated route discovery process with the known location information of the source node. In MRP, one primary path and many alternate paths are discovered. The system model of MRP is presented in Section 2.2. The description and algorithm of MRP are discussed in Section 2.3. Simulation results are presented in Section 2.4 and finally, this chapter is summarized in Section 2.5.

2.2 System Model

2.2.1 Assumptions

The following assumptions are considered for the proposed protocol.

- Sensors and the base station (i.e., sink) are all stationary after deployment.
- The sensor nodes are uniformly distributed in the network field with random deployment.
- The sensors are homogeneous and have the same capabilities.
- Sensor nodes are battery powered, hence have limited energy.
- Sensor nodes can calculate their residual energy.
- Links are symmetric, i.e., the data speed or quantity is the same in both directions, averaged over time.

2.2.2 Network Model

We consider a set of sensor node Vn and a sink node in the network. Each sensor node $Vn_i(i = 1, ..., n)$ has the location information (x_i, y_i). The sleep mode is used for the sensor node to conserve the energy. The communication is accomplished between the sensor nodes using the Timeout Media Access Control (TMAC) [95] protocol. The sink node possesses unlimited computation, memory, and battery power. The sink node also contains the *id* and *location* of each sensor node. When the sink required the data from the source node, it constructs the route between them. The threshold energy is the minimum residual energy of a sensor node, beyond which; it cannot perform any additional functions except sensing and relaying the data.

2.2.3 Energy Model

The total energy consumption by the sensor node in the network is derived and used in the implementation of the proposed protocol. The transmitting and receiving energy cost for k bits over the distance of d meters are $E_{TX}(k,d)$ and $E_{RX}(k)$ respectively. The derivations of $E_{TX}(k,d)$ and $E_{RX}(k)$ are illustrated in the Equations (2.1) and (2.2).

$$E_{TX}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^{\gamma} \tag{2.1}$$

$$E_{RX}(k) = E_{elec} \times k \tag{2.2}$$

Here E_{elec} is the energy cost of the embedded circuit to transmit or receive a signal of one bit. E_{amp} denotes the energy consumption of the amplifier to maintain the radio for reliable transmission. By using the free space propagation model [96] the energy cost on amplifier E_{amp} referred as:

$$E_{amp} = \varepsilon_{fs} \tag{2.3}$$

Here ε_{fs} is the energy cost of the amplifier to transmit one bit at an open space (one-hop). γ is the path-loss-exponent and the value of $\gamma \in \{2,4\}$ [97]. If the distance between the transmitter and recipient is d meter and threshold value of the distance is d_0 then;

$$\gamma = \begin{cases} 2 & \text{if,} \quad d \leq d_0 \\ 4 & \text{if,} \quad d > d_0 \end{cases} \tag{2.4}$$

d_0 can be denoted as:

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{2.5}$$

Here ε_{mp} is the energy cost of the amplifier to transmit one bit at multi-hop model. Using Equations (2.3) to (2.5), Equation (2.1) can be rewritten as:

$$E_{TX}(k,d) = \begin{cases} E_{elec} \times k + E_{amp} \times k \times d^2 & \text{if,} \quad d \leq d_0 \\ E_{elec} \times k + E_{amp} \times k \times d^4 & \text{if,} \quad d > d_0 \end{cases} \tag{2.6}$$

The energy spent by the sensor node in the sleep mode is:

$$E_{sleep}(t) = E_{low} \times t \tag{2.7}$$

Where E_{low} is the energy consumption of any node in sleep mode for one second. The total time spent in the sleep mode is t seconds. So the total energy consumption by a sensor node in the network is:

$$E_{Total} = E_{TX}(k, d) + E_{RX}(k) + E_{sleep}(t) \tag{2.8}$$

2.2.4 Performance Metrics

The efficacy of the proposed protocol has been demonstrated by using the standard performance metrics like control packet overhead, energy consumption, end-to-end latency, packet delivery ratio and network lifetime.

- **Control Packet Overhead:** It is the energy consumption at each sensor node due to the transmission and reception of control packets. These packets are not data. The control packets are used in neighbor discovery, route construction, cluster formation, maintenance process, and so on. This metric called an overhead because the packet transmission and reception, other than data is a burden to the network.

- **Energy Consumption:** It is the total energy consumption at each sensor node due to transmitting, receiving, listening, processing and sleeping. The routing protocol computes the energy consumption based on the energy model. This metric indicates, how efficiently a protocol works in the network.

- **End-to-End Latency:** The end-to-end latency is measured as the time taken for a data packet to transmit over a network from source to sink. It considers all types of delay such as queuing delay, route discovery delay, processing delay, and so on. This metric indicates the robustness of the routing protocol.

- **Packet Delivery Ratio:** It is measured as the ratio of the data packet received at the sink to the data packet sent by the sensor nodes. It defines the successful delivery of the data. The protocol with the better delivery ratio is considered to be consistent. This metric also signifies the reliability of the routing protocol.

- **Network Lifetime:** This metric indicates the duration for which the sensor network is fully functional. It depends on different applications. The lifetime of the network can be a time span when the first sensor dies, a percentage of sensors die, the network partitions, or the loss of coverage occurs. From the perspective of the network layer, the control packets exchanged for route discovery, establishment, and maintenance reflected the routing overhead, and it directly affects the network lifetime.

2.3 The Proposed Protocol

With the above assumptions, the working principle of the proposed protocol (MRP) is presented in this section. MRP avoids the flooding and takes the benefit of both load balancing and collision aware mechanism for energy conservation of the network. It mainly consists of four phases: neighbor discovery, multipath construction, data transmission and rerouting and route maintenance.

2.3.1 Neighbor Discovery

In this phase, each sensor node finds the neighboring nodes and maintains the neighbor's information as illustrated in the Algorithm 2.1. The initiator node broadcasts a control packet `NBR_DET`, which contains the node *id*, residual energy and the location of the node. The initiator node has been chosen randomly in the network, because initially all node's residual energy is the same. The neighbor node that receives the `NBR_DET` packet will maintain a table called $NbrTable$. The $NbrTable$ consists of node *id* of the sender node, its residual energy, and location. If the sender node *id* is already in the $NbrTable$, then the packet is dropped by the recipient node. The recipient node broadcasts the `NBR_DET` control packet if it does not broadcast before. After the neighbor discovery phase, each node has a list of its neighbor nodes.

Lemma 2.1. *The message complexity of neighbor discovery is $O(k)$, where k is the number of neighbors.*

Proof. In MRP, each node broadcasts the control packet once to get the neighbor information. If a node has k number of neighbors, it receives k number of control packets by each neighbor, so the message complexity in neighbor discovery is $O(k)$. □

Algorithm 2.1 **Neighbor Discovery**

Data Structure for any sensor node x :
$Nbr(x)$: neighbor set of node x, initialized to ϕ.
Er_x: residual energy of node x.
Loc_x: location information of node x.
$NbrTable(x)$: neighbor table of node x, initialized to ϕ.
$NbrDETSent_x$: set to **true** when the sensor node x sends `NBR_DET` packet, initialized to **false**.

```
node x receives following packet from node y:

NBR_DET :< NBR_DET, id_y, Er_y, Loc_y >
if (y ∉ Nbr(x)) then
    Nbr(x) ← Nbr(x) ∪ {y};
    Update NbrTable(x) with < id_y, Er_y, Loc_y >;
    if (NbrDETSent_x == false) then
        NbrDETSent_x ← true;
        l_rb(NBR_DET, id_x, Er_x, Loc_x);          ▷ Broadcast NBR_DET packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

2.3.2 Multipath Construction

After the neighbor discovery phase, each node possesses their neighbors' information. It is assumed that the sink knows the location of the source node in prior. The sink initiates the route discovery, based on the location of the source. There are two types of nodes *primary* and *alternate*. As described in the Algorithm 2.2, the primary node selects two nodes close to the source; one is called primary node, and another is called alternate node. This definition is recursively used in the algorithm. The primary path is built with the best possible neighbor (having the maximum Location Factor (LF) with sufficient residual energy), and the alternate path is constructed with the next-best neighbor (having the next maximum location factor after the primary path node with sufficient residual energy). The alternate node finds a node close to the source node. It searches the neighbor table for the node with the maximum location factor and preferably a primary node. This will ensure the path always converges.

Lemma 2.2. *Optimal selection of primary and alternate nodes, reduces the path length.*

Proof. In MRP, a primary and an alternate node are selected for the multipath construction. The selection of nodes are based on distance and residual energy from the source node, i.e., the neighbor node having the minimum distance and maximum residual energy is considered as the primary and next-best is considered as the alternate node using the Location Factor denoted by $LF(i)$ with the Equations (2.9) and (2.10). Let node i required to select the primary and alternate nodes from its neighbors. $Nbr(i)$ is the set of neighbors of a node i. $LF(i)$ is the set of location factors of each member of $Nbr(i)$. Er_k is the residual energy of node $k \in Nbr(i)$. (x_k, y_k) is the location information of node $k \in Nbr(i)$ and D_k is the Euclidean distance from the source node.

$$\text{Let, } Er_{\max} = \max_{k \in Nbr(i)} Er$$

then for k^{th} neighbor LF_k can be computed as

$$LF_k = \hat{E}r_k \times \frac{1}{D_k} = \frac{\hat{E}r_k}{D_k} \quad \forall k : k \in Nbr(i) \tag{2.9}$$

$$\begin{aligned} &where, \\ &\hat{E}r_k = \tfrac{Er_k}{Er_{\max}} \\ &D_k = \sqrt{(x_{source} - x_k)^2 + (y_{source} - y_k)^2} \end{aligned}$$

and,

$$next\_node_i = \max(LF(i)) \tag{2.10}$$

where, $next\_node_i$ is the primary or alternate node selected by the node i and this optimal selection technique reduces the path length. □

As shown in Figure 2.1(a), node a which is connected by bold line has the maximum location factor, signifies a primary node and is in the primary path close to the source. Similarly node b is connected by dashed line has the second highest location factor is the alternate node and is the part of the alternate path. All the

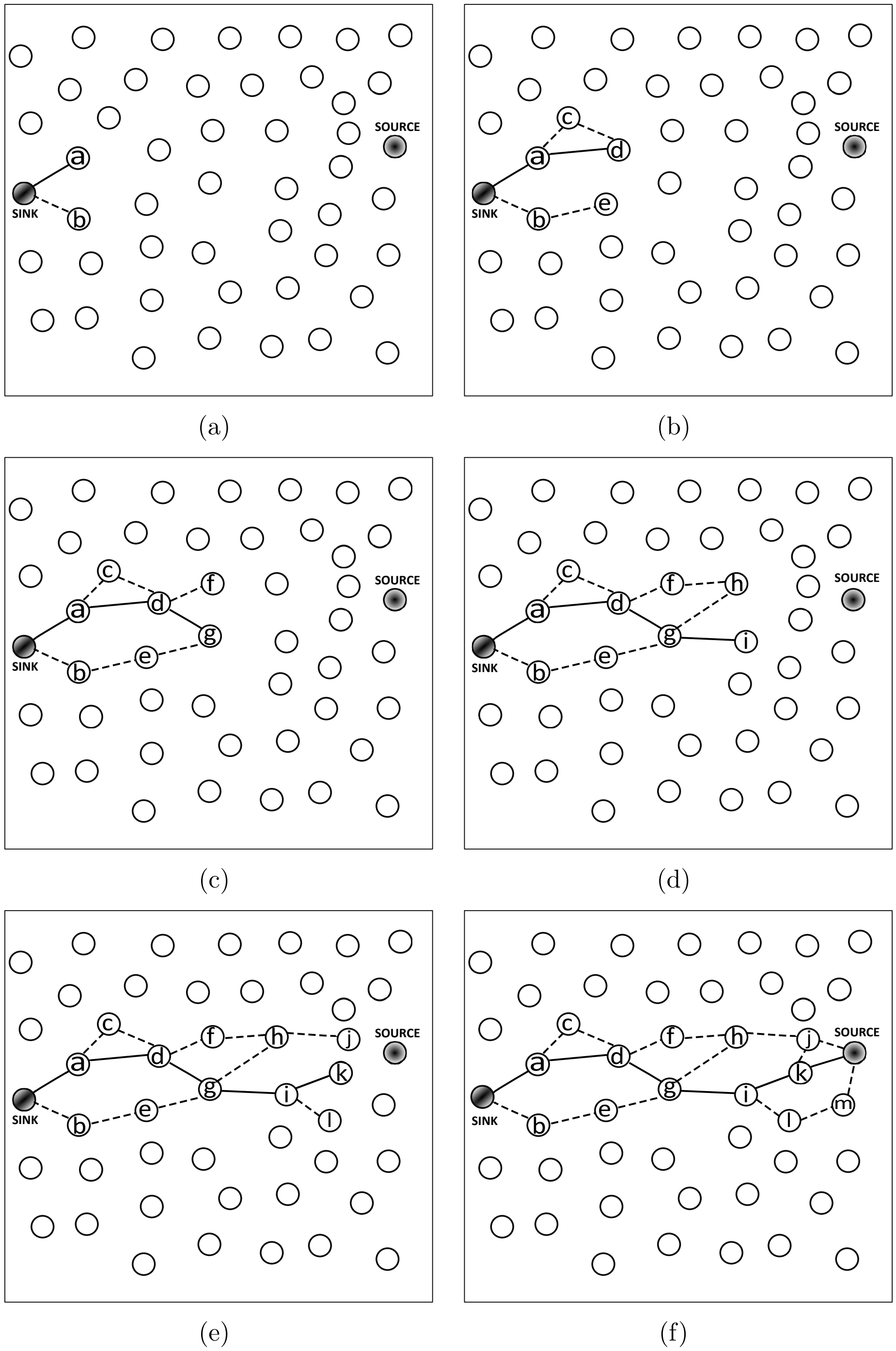


Figure 2.1: Multipath Construction steps shown in (a),(b),(c),(d),(e) and (f).

intermediate nodes follow the same process until the source node is found. One primary path and multiple alternate paths are constructed between the sink and the source node as illustrated in Figures 2.1. The paths are partially node-disjoint in the MRP. The process of multipath construction is presented in the Algorithm

Algorithm 2.2 **Multipath Construction**

Input: n number of sensor nodes randomly distributed.
Output: One primary and alternate paths from the source to the sink.

```
sink ← Primary;
repeat
    if (node == Primary) then
        FindPrimaryPath();
        FindAlternatePath();
    else if (node == Alternate) then
        FindPrimaryPath();
    end if
until (next_node ≠ Source)

procedure FindPrimaryPath()
    if (node == Primary) then
        Broadcast PRIMARY;
        choose the next_node to become the primary node by using the equations 2.9 and 2.10;
        next_node ← Primary;
        unicast the intimation message to the next_node;
    end if
    if (node == Alternate) then
        Broadcast ALTERNATE;
        choose the next_node by using the equations 2.9 and 2.10;
        if (next_node ≠ Primary) then
            next_node ← Alternate;
            unicast the intimation message to the next_node;
        end if
    end if
end procedure

procedure FindAlternatePath()
    if (node == primary) then
        choose the next_node accept primary by using the equations 2.9 and 2.10;
        next_node ← Alternate;
        unicast the intimation message to the next_node;
    end if
end procedure
```

2.2.

The Algorithm 2.2 has two procedures $FindPrimaryPath()$ and $FindAlternatePath()$ which are repeated until the source node is found as the $next\_node$.

- $FindPrimaryPath()$**:** This function is invoked by both primary and the alternate nodes. If the node is a primary node, it will broadcast its *id* with the `PRIMARY` control packet to inform the neighbors. The primary node selects $next\_node$ with maximum location factor using the Equations 2.9 and 2.10 and labeled as a primary node. Then it intimates about the status of the $next\_node$ by unicasting a message. Similarly, the alternate node will broadcast its *id* with the `ALTERNATE` control packet to inform the neighbors. The alternate node selects the $next\_node$ with maximum location factor using the Equations 2.9 and 2.10 and preferably a primary node. Otherwise, it labeled as an alternate node. Then the *next_node* is intimated about its status by unicasting a message. In both the cases, the *next_node* can have three possibilities. The node can be a primary node, alternate node or unassigned.

- *FindAlternatePath*(): This function is called only by the primary node to find an alternate path close to the source. It finds the next-best node as *next_node* which is called alternate node.

  All the nodes except the primary nodes are switched to sleep mode. At a time, only one path will be active between the source node and the sink. This reduces the interference from any other path and avoids the collision. Both these factors contribute to reducing the energy consumption. If the primary path gets disrupted, the protocol selects the alternate path to transmit data. However, if all the paths are disrupted, then the routing process starts over again from the neighbor discovery phase.

2.3.3 Data Transmission

After the route discovery phase, the sink node sends a request to the source node for data transmission. The sink initially chooses the primary node for the request. When the request received by the next primary node, it builds a reverse link to the preceding node to forward the data packet. In this way, the request reaches to the source, and the source node replies with the data packet. So each primary node has the next primary or alternate node to choose. Generally, the source node transmits the data over the primary path. However, the alternate paths are used when the primary path is not available. The nodes that are not in the active path will switch to the sleep mode to conserve the energy. If no path exists between the source and the sink, then the routing process starts once again.

Lemma 2.3. *The data forwarding delay reduces by the optimal multipath routes.*

Proof. Considering Lemma 2.2, the optimal paths are used in the MRP. Let, d

is the distance from the destination node, c is the speed of light, L is the data packet length, B is the bandwidth, and T_{extra} is the processing and queuing time. Then, the data forwarding delay in the primary path can be formulated as

$$T_{primary} = \sum \frac{d}{c} + \sum d \frac{L}{B} + \sum T_{extra} \tag{2.11}$$

So, the delay will be reduced with respect to the d value. □

Lemma 2.4. *The time complexity to send a packet from the source to sink is $O(m)$, where m is the number of nodes in the optimal path.*

Proof. The MRP constructs optimal multipath from the source to the sink. At each iteration, one path is used for data transmission. The path length is m, where m number of nodes across the path. Each node will forward the data. In other words, each node receives the data from the preceding node, processes it and transmits to the next node. Hence, the time complexity is $O(m)$. □

Lemma 2.5. *The total message complexity of the network is $O(nk)$.*

Proof. Let n number of sensor nodes are deployed in the network. According to Lemma 2.1, for neighbor discovery phase message complexity of a sensor node is $O(k)$, where k is the number of neighbors. For the multipath construction, Let 'p' number of primary nodes and 'a' number of alternate nodes are used, where $(p + a) < n$. The message complexity for the primary and alternate nodes is $O(3p + 2a)$. Primary node uses one broadcast message and two unicast message, whereas alternate node uses one broadcast message and one unicast message. For the route reply, the routing protocol using 'p' number of messages. The total message in the network is represented as $(nk + 3p + 2a + p)$. Hence, the total message complexity of the network is $O(nk)$. □

2.3.4 Rerouting and Route Maintenance

In this protocol, the route discovery process starts by the sink. So it is the responsibility of the sink to maintain the available paths and initiate the rerouting process. In the active path if any sensor node's residual energy goes below the threshold, then it informs the sink by sending a control signal. So that the sink sends a `SWITCH` control packet with that node *id* to consider another available path. Its *next_node* will choose another available node for data transmission. If there will be no path available, then the sink initiates the rerouting by invoking the neighbor discovery and multipath construction phase.

2.3.5 Energy Consumption Analysis

It is required to analyze the energy consumption of the proposed protocol at different stages and provide better scope to evaluate the performance of the protocol.

Lemma 2.6. $E_{total} = \sum(E_{TX}(k,d) + E_{RX}(k) + E_{sleep}(t))$ *is the total energy consumption in the network.*

Proof. In MRP, each node performs three operations such as transmitting, receiving, and sleeping. If $E_{TX(k,d)}$ is the transmission energy of k bit over a distance d, $E_{RX}(k)$ is the reception energy of k bit data, and $E_{sleep}(t)$ is the energy consumption in sleep mode during t second, then the total energy consumed by the network is

$$E_{Total} = \sum(E_{TX}(k,d) + E_{RX}(k) + E_{sleep}(t)) \tag{2.12}$$

□

Lemma 2.7. *The network lifetime is* $\min\left\{\frac{TE}{Ec_i}\right\}$, *where* $i = 1, 2, 3, ...n$.

Proof. The network lifetime is defined as the total number of packet communication causes the first node of the network to die. The sensor node dies due to the exhausted battery power. Let TE is the total energy given to every sensor nodes S_i. So S_i utilizes E_{ND} amount of energy for neighbor discovery, E_{MP} amount of energy for multipath construction, E_{DATA} amount of energy for data transmission and E_{PROC} amount of energy for other activities of the network. As it is assumed that all the sensor nodes are uniform in nature, the network lifetime in MRP is defined as

$$\min\left\{\frac{TE}{Ec_i}\right\}$$

where,

$$Ec_i = E_{ND_i} + E_{MP_i} + E_{DATA_i} + E_{PROC_i} \tag{2.13}$$

□

Lemma 2.8. *The expected energy requires for the reliable transmission of a packet from node i to node j is* $E_{ij(reliable)} = \frac{E_{ij}}{1-p_{ij}}$.

Proof. In MRP, let the energy required to transmit a packet once from node i to node j is E_{ij}. The packet-error probability is also required for reliable transmission between two nodes and let it be p_{ij}. So the error-free packet transmission is $(1 - p_{ij})$, and the expected number of re-transmission required from node i to node j is $\frac{1}{1-p_{ij}}$. Then the expected energy requires for the reliable transmission of a packet from node i to node j is

$$E_{ij(reliable)} = \frac{E_{ij}}{1-p_{ij}} \tag{2.14}$$

□

2.4 Simulation Results

The proposed protocol (MRP) is implemented using Castalia (v3.2) [98]. It is a simulator for WSN based upon the OMNeT++ platform [99]. The Maximally Radio-disjoint routing (MR2) [39] and Low Interference Energy-efficient Multipath ROuting (LIEMRO) [41] are also implemented to compare with the MRP. The simulation parameters are listed in the Table 2.1. The parameters have been taken as standardized for the MICAz Mote developed by Crossbow Technology, Inc. [100].

Parameter Name	**Value**
Network area	500×500 $meter^2$
Number of sensor nodes	100
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{low}	0.2 nJ/sec
Simulation time	400 *sec*
MAC protocol	TMAC

Table 2.1: Simulation Parameters.

2.4.1 Average Control Packet Overhead

MR2 floods the route request over the network. The request floods until the sensor node referred to as the source. The flooding increases the message complexity in the network and consumes the excessive amount of energy. In the LIEMRO, each node broadcasts and receives a certain number of control packets to evaluate the Expected Transmission Count (ETX) [42] cost, which further use in the route discovery process. However, the proposed protocol (MRP) neither uses flooding nor involving the entire network to discover the path. The sink initiates the route discovery by selecting two nodes (primary and alternate) towards the source by using the location information of the source. Thus, the control packet overhead is very less in MRP as compare to MR2 and LIEMRO as shown in Figure2.2.

It is also observed that the MR2 and LIEMRO gives the same result at the simulation time 250 seconds and 400 seconds. To test the behavior further, the simulation is performed with 200 nodes and up to 1800 seconds simulation time. The result is illustrated in Figure 2.3. It has been found that the energy consumption at each node is increasing uniformly with the simulation time.

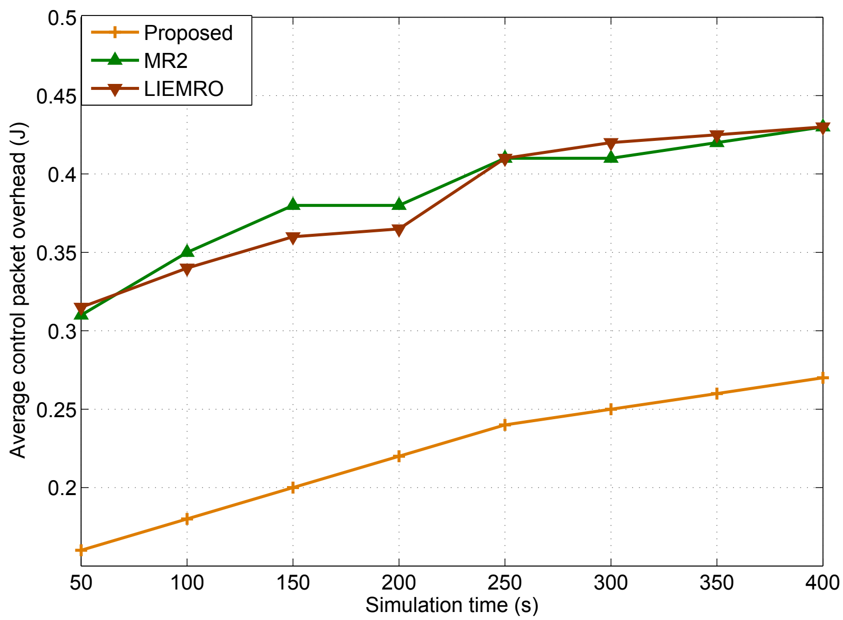


Figure 2.2: Average Control Packet Overhead.

2.4.2 Average Energy Consumption

The MR2 and LIEMRO both are suffering from excessive control packet overhead. So the average energy consumption is also high as compared to the proposed scheme. The result is shown in Figure 2.4.

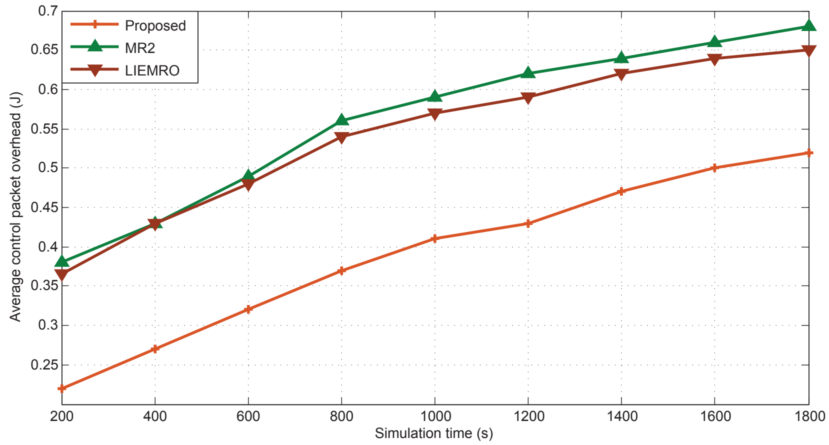


Figure 2.3: Average Control Packet Overhead (1800 sec and 200 nodes).

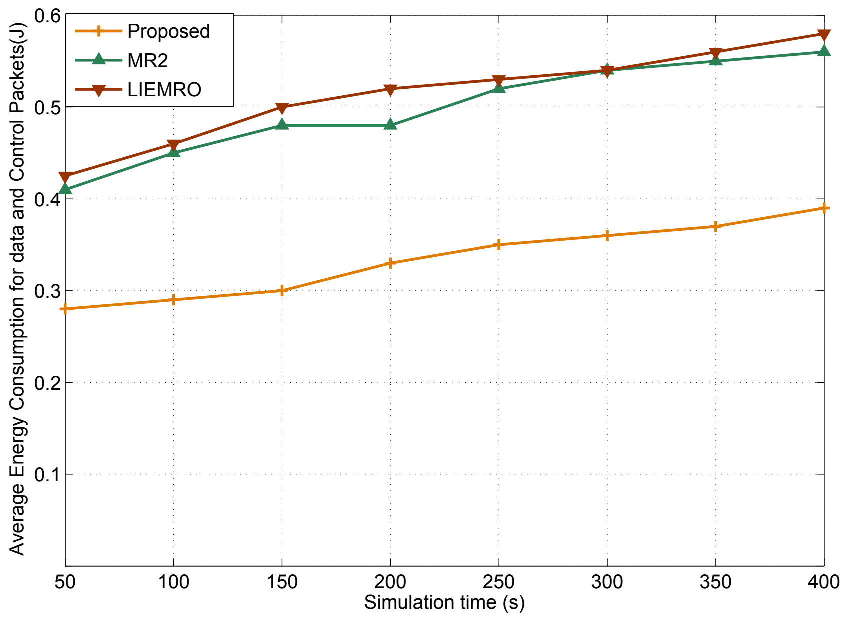


Figure 2.4: Average Energy Consumption.

2.4.3 Average End-to-End Latency

MR2 uses only one path at a time to transmit the data. When the path fails it starts discovering another path, which increases the latency. In the LIEMRO, the end-to-end latency is very less when the number of nodes in the network is less because it uses all the available path and distributes the data among the path. However, when the number of node raises, the interference also increases, which leads to the higher latency. Like MR2, the proposed scheme (MRP) also uses one path at a time to transmit the data, and due to available alternate paths, the latency is less. The result in Figure 2.5 shows that the data delivery latency of the proposed protocol is less than LIEMRO and MR2.

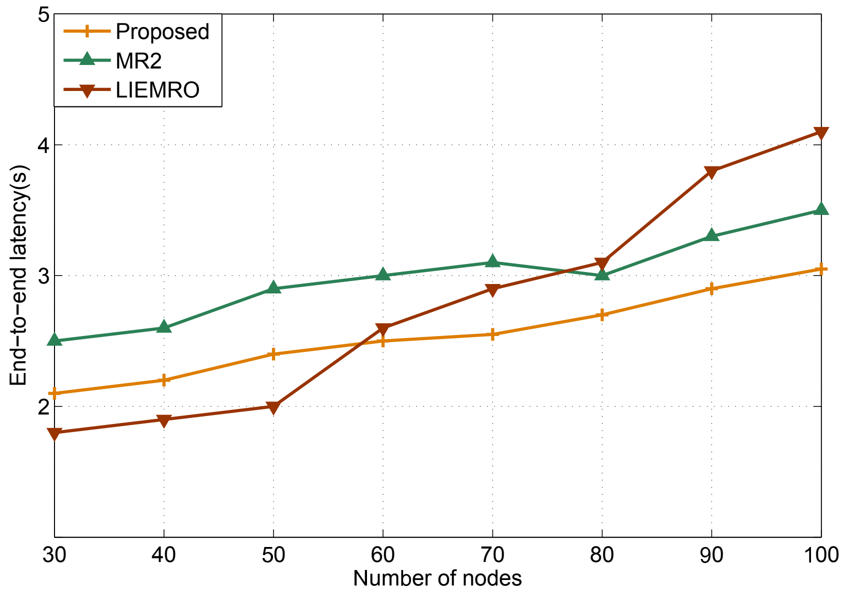


Figure 2.5: Average End-to-End Latency.

2.4.4 Packet Delivery Ratio

The result is illustrated in Figure 2.6. LIEMRO protocol distributes the load among the available path by assigning the different data rates. If a path fails, it disables the path and redistributes the network traffic over other active paths. Hence, the throughput of the network is maintained. Whereas MR2 uses one path at a time to transmit the data. If the path fails, it discovers another path. In the proposed protocol (MRP), one primary and many alternate paths are available. It uses one path at a time. The remaining energy of the node is observed. If, in the active path, any node found with the residual energy below the threshold, it shifted to another available path. Hence, the data loss is negligible. The proposed scheme gives the improved result up to 80 sensor nodes, but when the number of nodes increases the packet delivery ratio get decreases. Hence, to understand the performance of the proposed protocol the simulation has been performed with 1800 seconds simulation time and up to 200 sensor nodes. From the resulting Figure 2.7, it has been concluded that the proposed MRP protocol maintains the higher packet delivery ratio throughout the simulation.

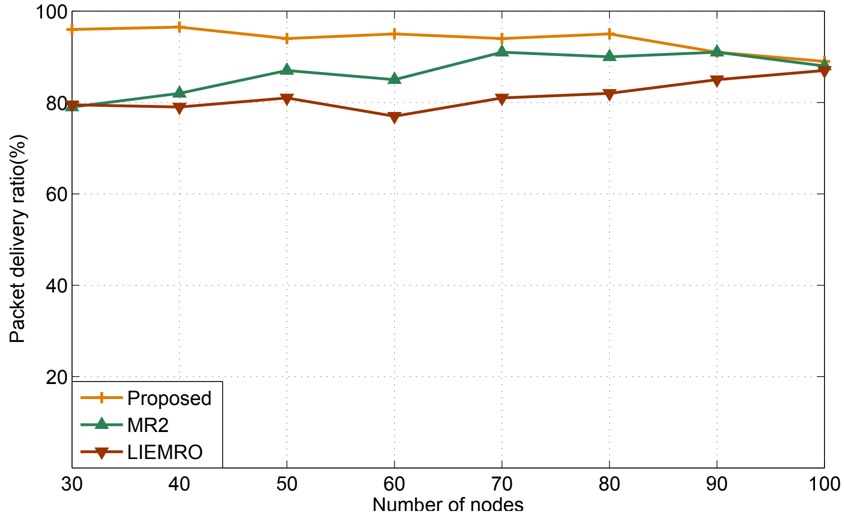


Figure 2.6: Packet Delivery Ratio.

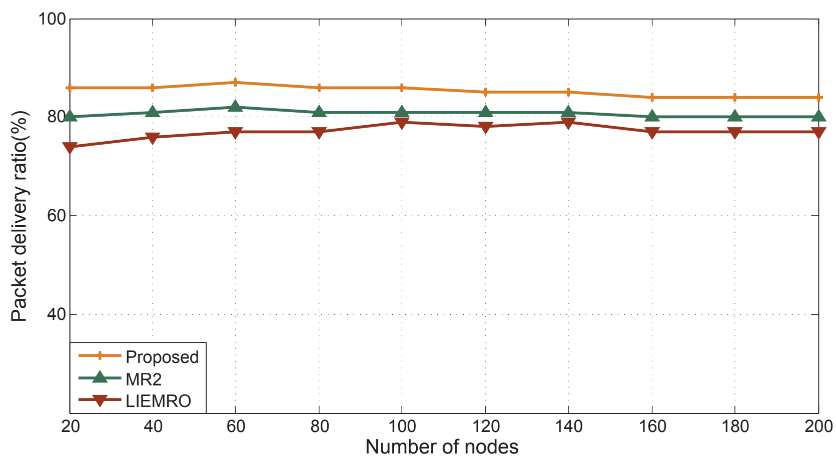


Figure 2.7: Packet Delivery Ratio (1800 sec and 200 nodes).

2.4.5 Network Lifetime

As shown in Figure 2.8, the network lifetime of the proposed scheme is greater than the MR2 and LIEMRO. The reason behind that is fewer control packets overhead and load balancing among the sensor nodes.

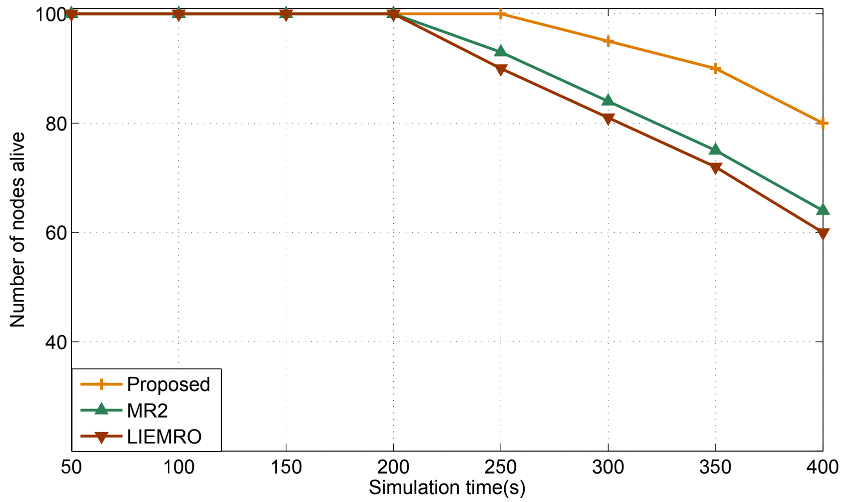


Figure 2.8: Network Lifetime.

2.5 Summary

The chapter proposed an energy-efficient and reliable multipath routing protocol. MRP discovered the multipath and maintained this with minimum control overhead, and using the load balancing mechanism. The simulation results are compared with the existing protocols based on metrics such as average control packet overhead, average energy consumption, latency, packet delivery ratio and lifetime. It has been found that the proposed protocol outperformed the existing protocols.

Chapter 3

Cluster based Multipath Routing Protocol with Static Sink

Chapter 3

Cluster based Multipath Routing Protocol with Static Sink

3.1 Introduction

The sensor node transmits the data to the base station through the intermediate sensor nodes in the multihop environment. In the sensor network with energy constraint environment, the network often requires energy-efficient routing protocol. The reliable path significantly reduces the re-transmission of data, which can decrease congestion and energy consumption. Generally, sensor nodes are densely deployed in the network, and a coverage area might be overlapped by many sensor nodes, which generate duplicate data. In multipath routing protocol (MRP) as discussed in the Chapter 2 provides the reliability, but the sink receives redundant data. This problem can be resolved by using the clustering technique. In clustering, the cluster heads aggregate the cluster members' data before transmitting to the sink. The clustering reduces the data traffic in the network, and multipath technique provides the reliable path. These two techniques motivate to propose a hybrid protocol that has the benefit of both clustering and multipath.

In this chapter, Cluster based Multipath Routing Protocol (CMRP) is proposed, which addresses the requirements as mentioned above. The major drawback of the existing protocols [15, 53] is the control packet overhead. To decrease the overhead, the CMRP reduces the load on the sensor nodes and provides more responsibility to the sink, as the sink is a resource-rich node. The system model of CMRP is described in Section 3.2. The algorithm of the proposed model is discussed in Section 3.3. In Section 3.4 simulation parameters, results and analysis are discussed. Finally, the summary of this chapter is presented in Section 3.5.

3.2 System Model

3.2.1 Network Model

The WSN is the combination of large sensor nodes and the communication link between them within the radio range R. It is the bidirectional link between two nodes v_i and v_j. If the distance between two nodes is $d(v_i, v_j) \leq R$, then the communication link will be considered as direct (one-hop) otherwise indirect (multi-hop). Addition to the assumptions made in the Chapter 2, a wireless sensor network that consists of n number of sensor nodes, and a base station have been considered. The base station acquires unlimited memory, computation and battery power. Nodes can estimate the RSSI value of the received signal. This protocol is suitable for the periodic sensing applications.

3.2.2 Energy Model

In this chapter, the same energy model as specified in Chapter 2 from Equations (2.1) to (2.7) have been considered.
The energy spent by the cluster head in the data aggregation is derived as:

$$E_{agg}(k) = E_{proc} \times k \tag{3.1}$$

Where E_{proc} is the processing cost of one-bit of data, and k is the data size in bits. So the total energy consumption by a sensor node in the network is derived using Equations (2.1), (2.6), (2.7) and (3.1)

$$E_{Total} = E_{TX}(k, d) + E_{RX}(k) + E_{agg}(k) + E_{sleep}(t) \tag{3.2}$$

3.3 The Proposed Protocol

The proposed protocol CMRP is a proactive routing protocol, in which all the paths are discovered prior to its requirement. This approach is suitable for the static network. CMRP is a cluster-based routing protocol that requires the route from the cluster head to the base station. The base station is responsible for computing the routing path and monitoring the energy level of each sensor node in the network. It consists of four phases: neighbor discovery and topology construction, cluster head selection and cluster formation, data transmission, and re-clustering and rerouting.

3.3.1 Neighbor Discovery and Topology Construction

The base station initiates neighbor discovery phase after the deployment of sensor nodes. Here each sensor node will broadcast `NBR_DET` packet once. At the end of the neighbor discovery phase, each node has the information about their neighbors. Each node broadcasts the `NBR_DET` control packet as shown in Figure 3.1. The `NBR_DET` packet consists of sender *id*. Whenever a node receives the `NBR_DET` packet, it does the following operations:

1. Checks the neighbor list for the existence of the sender node *id*. If the sender *id* is not available in the neighbor list, then add it, else drops the packet.

2. If $NbrDETSent$ is false, then recipient node makes $NbrDETSent$ as true and broadcasts the `NBR_DET` packet.

The above operations are illustrated in Algorithm 3.1. After the neighbor discovery phase, topology construction phase starts. In this phase, each node transmits their neighbor information to the base station. For this, each node uses multicasting technique instead of flooding. The nodes start sending the neighbor information to the base station through relay nodes as shown in Figure 3.2. The sender node chooses the relay node from $Nbr(x)$ and forwards the neighbor information to the base station as described in the Algorithm 3.1. A sensor node will forward the `Nbr_INFO` packet only once, to avoid looping in

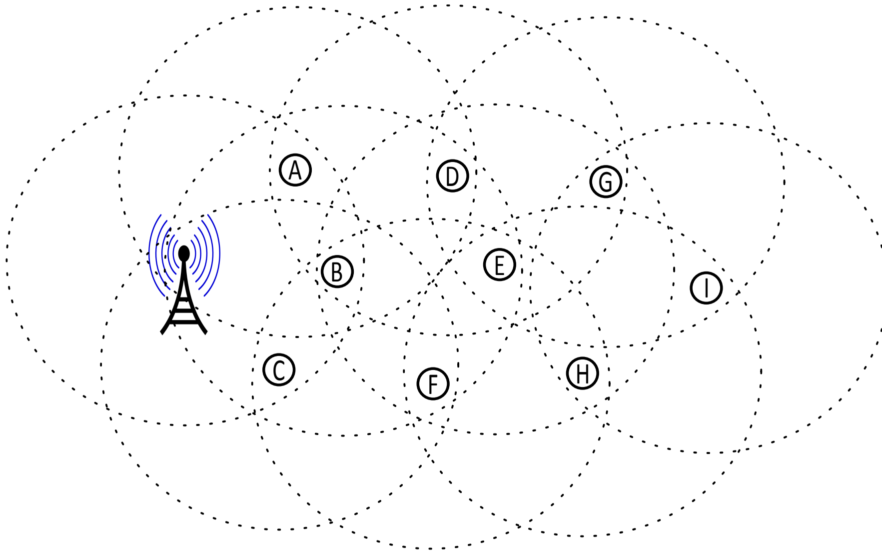


Figure 3.1: Neighbor Discovery.

Algorithm 3.1 **Neighbor Discovery and Topology Construction**
Data Structure for any sensor node x :
$Nbr(x)$: neighbor set of node x, initialized to ϕ.
$NbrDETSent_x$: set to **true** when the sensor node x sends `NBR_DET` packet, initialized to **false**.
$ReceivedNbrINFO(x)$: set of nodes by which node x received the `Nbr_INFO` packet, initialized to ϕ.

```
node x receives following packet from node y:

NBR_DET :< NBR_DET, id_y >
if (y ∉ Nbr(x)) then
    Nbr(x) ← Nbr(x) ∪ {y};
    if (NbrDETSent_x == false) then
        NbrDETSent_x ← true;
        l_rb(NBR_DET, id_x);                                  ▷ Broadcast NBR_DET packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if

Nbr_INFO :< Nbr_INFO, Nbr(y), id_y, Relay_id >
if (Relay_id == id_x) then
    if (y ∉ ReceivedNbrINFO(x)) then
        ReceivedNbrINFO(x) ← ReceivedNbrINFO(x) ∪ {y};
        if (id_x == id_BS) then
            Update the neighbor adjacency matrix using Nbr(y);
        else
            l_rf(Nbr_INFO, Nbr(y), id_y, Relay_id);   ▷ Forward the Nbr_INFO packet to the selected relay node
        end if
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

the network. For doing this, each node maintains a received neighbor information list. Therefore, it reduces the traffic in the network and conserves the energy. The

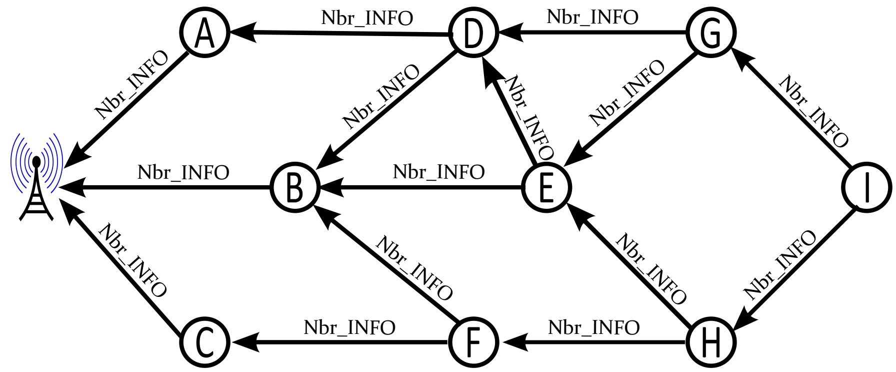


Figure 3.2: Nodes send the Nbr_INFO packet to the base station.

	BS	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
BS	0	1	1	1	0	0	0	0	0	0
A	1	0	1	0	1	0	0	0	0	0
B	1	1	0	1	1	1	1	0	0	0
C	1	0	1	0	0	0	1	0	0	0
D	0	1	1	0	0	1	0	1	0	0
E	0	0	1	0	1	0	1	1	1	0
F	0	0	1	1	0	1	0	0	1	0
G	0	0	0	0	1	1	0	0	0	1
H	0	0	0	0	0	1	1	0	0	0
I	0	0	0	0	0	0	0	1	1	0

Table 3.1: Neighbor Adjacency Matrix.

base station creates the neighbor adjacency matrix when it receives the `Nbr_INFO` from the sensor nodes. Neighbor adjacency matrix is shown in Table 3.1. It is a $(n+1) \times (n+1)$ matrix, where n is the number of nodes in the network and a base station. The neighbor adjacency matrix shows the network topology and connectivity of the nodes. Based on neighbor adjacency matrix, the base station selects the cluster heads and routing paths from each cluster head to the base station.

3.3.2 Cluster Head Selection and Cluster Formation

After neighbor discovery and topology construction, the formation of the cluster is started. Initially, all nodes' energy levels are the same. After the formation of the neighbor adjacency matrix, the base station will compute and monitor the residual energy of each node. The base station chooses a certain number of cluster heads in the network using the following conditions:

1. Two cluster heads should not be neighbor to each other,

    Let CH is a set of all cluster heads and $x \in CH$

    $Nbr(x)$ is a set of one hop neighbors of x

    if $(y \in Nbr(x))$ **then**

    $y \notin CH$ ▷ This is the first condition for any node to be a cluster head

    end if

2. the residual energy (Er) of each cluster head should be greater than threshold value.

    Let $E_{threshold}$ is the threshold energy and

    Er_x is the residual energy of node x

    if $(Er_x \geq E_{threshold})$ **then**

    $x \in CH$ ▷ This is the second condition for any node to be a cluster head

    end if

3. and each cluster head should have at least $\frac{k}{2}$ number of nodes as neighbor.

    Let a is the alive nodes and

    m is the optimal number of cluster heads in the network

    Then, $k = \frac{a-m}{m}$ ▷ k is the average number of nodes in a cluster in the ideal case

    So that, $Nbr(x) \geq \frac{k}{2}$ ▷ This is the third condition for any node to be a cluster head

The selection of a cluster head depends on two independent factors; one is the residual energy (Er), and another is the degree of the node, i.e., the number of neighbor nodes.

Lemma 3.1. *At most one cluster head is selected in the radio range R.*

Proof. In CMRP, the sink selects the cluster head with the condition that two cluster head will not be the neighbor of each other. In other words, in the cluster head range R there should not be any other cluster head. Sink selects the cluster head based on the neighbor list of each node. Let CH is the set of all cluster heads and a node $x \in CH$, $Nbr(x)$ is the set of one-hop neighbors of x.

$$\textbf{if}\,(y \in Nbr(x))\ \textbf{then}$$

$$y \notin CH$$

□

Lemma 3.2. *Expected number of nodes within the cluster head radio range R is $\left\lceil \left(\frac{\pi R^2}{|A|}\right) \times n \right\rceil$.*

Proof. Let, n_{exp} is the expected number of the nodes within the cluster range R. The area a cluster head can cover is πR^2, and the network area are defined as $A(m \times m)$. If the number of sensor nodes in the network is n, then the expected number of nodes within the cluster head radio range is

$$n_{exp} = \left\lceil \left(\frac{\pi R^2}{|A|}\right) \times n \right\rceil \tag{3.3}$$

□

Lemma 3.3. *CH_{req} number of cluster heads can cover the entire network.*

Proof. Considering Lemma 3.2, the expected number of nodes within the network is n_{exp}. Let, CH_{req} is the required number of cluster heads to cover the entire network then,

$$n = CH_{req} + (CH_{req} \times n_{exp}) \tag{3.4}$$

$$n = (1 + n_{exp}) \times CH_{req} \tag{3.5}$$

so,

$$CH_{req} = \frac{n}{(1 + n_{exp})} \tag{3.6}$$

Hence, The entire network can be covered using CH_{req} number of cluster heads.

□

After selecting the cluster head, the base station determines the path between the cluster head and the base station. The base station refers to the neighbor adjacency matrix and ensures the following selection criteria for routing path:

1. The residual energy of the sensor node in the path should be greater than the threshold value,

   Let P is a set of nodes in the path

   and Er_x is the residual energy $x \in P$ then

   $Er_x \geq E_{threshold}$ ▷ This is the first condition for routing path selection

2. and the total energy consumption of the routing path should be minimum.

   Let $\mid P \mid$ is the number of nodes in the path and

   $\{P_1,\ P_2,\ P_3,\ ....P_j\}$ are the available paths from the cluster head to the base station.

   So, $P = \min_{1 \leq i \leq j}(\mid P_i \mid)$ ▷ This is the second condition for routing path selection

---

Algorithm 3.2 **Cluster Head Intimation**

Data Structure for any sensor node x :
$PATH(x)$: set of sensor nodes involved in the path between the node x and the base station.
$RTable(x)$: the routing table maintained by each relay node having two columns cluster head *id* and *next_hop*, initialized to ϕ.

```
node x receives following packet from node y:

CH_INT :< CH_INT, id_y, PATH(ch), id_ch >
if (id_ch == id_x) then
    l_rf(ACK, id_x, next_hop);                    ▷ Forward the ACK packet to the base station
else
    if (x ∈ PATH(ch)  &&  id_ch ∉ RTable(x)) then
        Update the RTable(x) by adding cluster head id as id_ch and next_hop as id_y;
        l_rb(CH_INT, id_x, PATH(ch), id_ch);      ▷ Broadcast CH_INT packet
    else
        Drop the packet;
    end if
end if

ACK :< ACK, id_y, next_hop >
if (next_hop == id_x) then
    if (id_x == id_BS) then
        Time_out ← false;
    else
        Look up the RTable(x) and find the next_hop of cluster head y;
        l_rf(ACK, id_y, next_hop);                ▷ Forward the ACK packet towards the base station
    end if
else
    Drop the packet;
end if
```

To notify the sensor nodes that have been chosen as a cluster head, the base station unicasts the intimation packet (CH_INT) to the cluster heads using the selected path as illustrated in the Algorithm 3.2. The CH_INT packet follows the path and reaches the cluster head. The sensor nodes involved in the path make a reverse link towards the sink to relay the data from the cluster head. When the cluster head receives the `CH_INT` packet, it sends back an acknowledgment (`ACK`) packet to the base station. The `ACK` packet follows the same reverse path from where `CH_INT` packet came. The base station selects another path if it does not receive the `ACK` packet from the cluster head within a predefined time duration.

Afterwards, cluster head broadcasts the advertisement packet to form a cluster as illustrated in the Algorithm 3.3. Nodes that receive more than one advertisement will choose the cluster head based on higher RSSI (Received Signal Strength Indication). After selecting the cluster head, a node sends the joining request in the format `CH_JOIN` packet. The cluster head receives similar `CH_JOIN` packets from each interested node. After receiving all the joining requests, the cluster head transmits the information of the cluster members to the base station. For reducing the congestion, the cluster head generates the time-slot schedule for the cluster members based on Time Division Multiple Access (TDMA) [101] and send to the cluster members. The TDMA time-slot is used for the collision-free communication between the cluster member and the cluster head.

Algorithm 3.3 Cluster Formation

Data Structure for any sensor node x :
$RSSI(x)$: set of received signal strength of the sender nodes, initialized to ϕ.
$CHSelected_x$: set to **true** when the sensor node x selected the cluster head, initialized to **false**.
$ChMbr(x)$: set of cluster members of any *cluster head* x, initialized to ϕ.

node x receives following packet from node y: where $x \notin CH$ and $y \in CH$

```
CH_ADV :< CH_ADV, id_y >;
RSSI(x) ← RSSI(x) ∪ RSSI_y;
After receiving all CH_ADV, node x chooses a node with highest received signal strength as its cluster head.
CHSelected_x ← true;
l_rf(CH_JOIN, id_x, id_ch);                ▷ Send the join request to the cluster head
```

node x receives following packet from node y: where $x \in CH$ and $y \notin CH$

```
CH_JOIN :< CH_JOIN, id_y, id_ch >
if (id_x == id_ch) then
    ChMbr(x) ← ChMbr(x) ∪ y;
    After receiving all CH_JOIN, node x sends the ChMbr(x) to the base station.
    Broadcast the time-slot schedule to the cluster members.
else
    Drop the packet;
end if
```

Lemma 3.4. *The cluster formation requires $O(n)$ control messages.*

Proof. At the beginning, each node broadcasts a `NBR_DET` packet. Thus, there are n messages in the network. Each node transmits its neighbor information to the sink that again takes n messages. Each cluster member broadcast a `CH_JOIN` packet to join the cluster head. Suppose the number of generated cluster heads are α. So the total number of join request is $(n - \alpha)$ and for time-slot α messages are required by the cluster heads. Thus the total number of control messages in cluster formation requires $n + (n - \alpha) + \alpha + \alpha = 2n + \alpha$. Therefore, the overall complexity of the control message in the network for cluster formation is $O(n)$. □

Lemma 3.5. $E_{total} = \sum((E_{CH} \times (\alpha)) + (E_{CM} \times (1 - \alpha)))$ *is the total energy consumption in the network.*

Proof. In CMRP, each node is divided into two category cluster head and cluster members. Cluster members transmit their data to the cluster head, and cluster head aggregates the data and transmits to the sink. The individual cluster head consumes E_{CH} energy in the transmission, reception and aggregation. Cluster member consumes E_{CM} energy in the transmission, reception and sleeping. Let α is the number of cluster head in the network, and then the total energy consumption in the network is

$$E_{total} = \sum((E_{CH} \times (\alpha)) + (E_{CM} \times (1 - \alpha))) \tag{3.7}$$

□

3.3.3 Data Transmission

The cluster member transmits the generated data to the cluster head based on the given time slot and then changes the operational mode to sleep mode. The sensor node wakes up in the next time slot to transmit the data. In this way, the protocol helps in conserving the energy of the sensor nodes. The cluster head aggregates the data and sends to the base station through the selected path. All intermediate relay nodes refer to the routing table for the next node to forward the data. When the data reaches the base station, an acknowledgment packet is sent back to the cluster head. If the cluster head does not receive the acknowledgment from the base station, it re-transmits the data. The base station monitors the residual energy of each node in the network as it has the entire information of network topology. If base station finds the residual energy of any node below the threshold value, it selects another available path for that cluster head.

3.3.4 Re-clustering and Rerouting

The base station initiates the process of re-clustering and rerouting. It monitors the residual energy of each sensor node in the network to balance the load among the sensor nodes. If the residual energy falls below the threshold value, the node initiates re-clustering or rerouting based on its role. If that node is a relay node of any path, then the base station selects another available path to exclude that node. If the node is a cluster head, then the base station selects another cluster head and the corresponding path. This method increases the lifetime of the networks. The node is having the residual energy below the threshold, neither take part in routing nor become a cluster head, but only operate as the cluster member.

3.4 Simulation Results

Through the simulation, the proposed CMRP performance is analyzed and compared with the existing protocols such as Fault Diagnosis based Clustering and Multipath routing protocol (FDCM) [15] and Practical Passive Cluster based Multipath Protocol (PPCMP) [53]. The performances of the protocols are compared based on the metrics such as control packet overhead, energy consumption, packet delivery ratio and network lifetime as specified in Chapter 2. The intensive set of simulation is performed using the Castalia (v3.2) simulator and based on the parameter illustrated in Table 3.2.

Parameter Name	Value
Network area	500×500 $meter^2$
Number of sensor nodes	100
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{proc}	5 nJ/bit
E_{low}	0.2 nJ/sec
Simulation time	400 *sec*
MAC protocol	TMAC

Table 3.2: Simulation Parameters

3.4.1 Average Control Packet Overhead

The control packet overhead by the various protocols is shown in Figure 3.3.

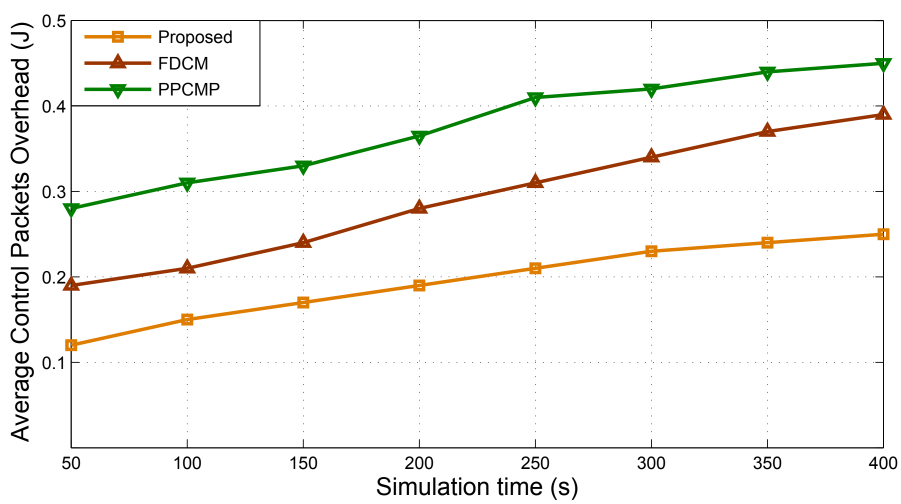


Figure 3.3: Average Control Packet Overhead.

It is observed that the control packet overhead is less for the proposed protocol (CMRP) as compared to PPCMP and FDCM. This is because the proposed scheme neither uses flooding nor involves the entire network in selecting the cluster heads and multipath. The sink itself selects the cluster heads and the routing paths. However, PPCMP constructs multipath by flooding the control packets over the network. This is the major cause for the increase in control packets overhead. Further, if any node becomes the source node, the multipath is reconstructed. This is an additional overhead of the protocol. In the cluster formation phase of FDCM, the exchange of test request and reply for testing the faulty node is an overhead. In multipath construction, the control packets are broadcasted in the increased range of $2R$ that also consumes more energy.

3.4.2 Average Energy Consumption

The average energy consumption by various protocols is illustrated in Figure 3.4. The average energy consumption by the proposed protocol (CMRP) is less as compared to PPCMP and FDCM. PPCMP uses the optimal path to transmit the data. However, due to increased control packet overhead, the average energy consumption is more. In FDCM, the control packet overhead is more, and the aggregated data are transmitted through the cluster heads with the range of $2R$. This increases the overall energy consumption as it takes twice the power to transmit the data as compared to the other protocol. However, in the proposed protocol, the control overhead is less as the sink itself selects the optimal path for the data transmission. Therefore, the average energy consumption is least.

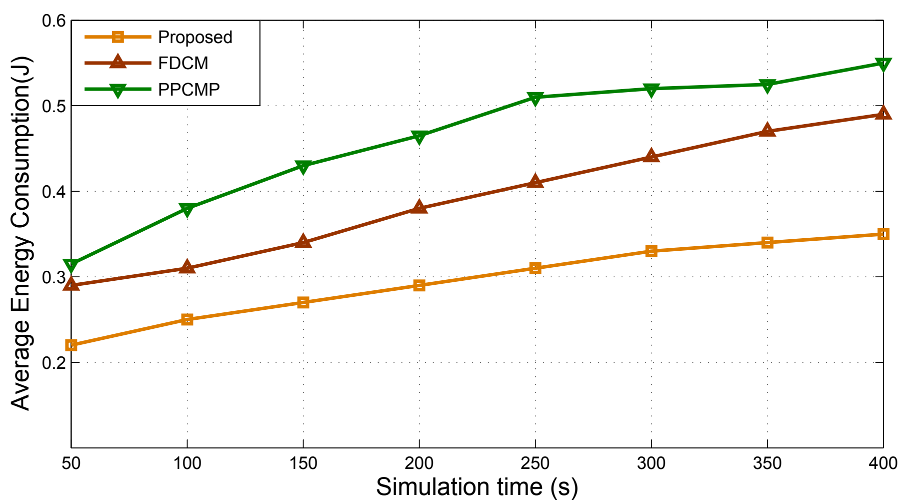


Figure 3.4: Average Energy Consumption.

3.4.3 Average End-to-End Latency

In the FDCM, due to available neighbor cluster head list the end-to-end delay is less. However, in a situation where the network has to choose a new cluster head, the selection process starts from the beginning, which increases the delay. Whereas, for the proposed scheme, the alternative paths are available. The result in Figure 3.5 shows that the end-to-end latency of the proposed scheme is less than the PPCMP and marginally lesser than the FDCM.

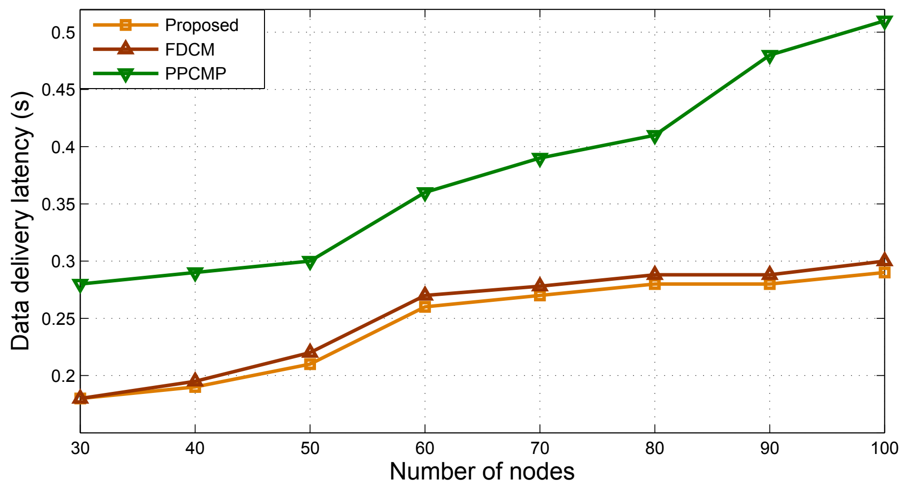


Figure 3.5: Average End-to-End Latency.

3.4.4 Packet Delivery Ratio

The packet delivery ratio of each protocol is depicted in Figure 3.6.

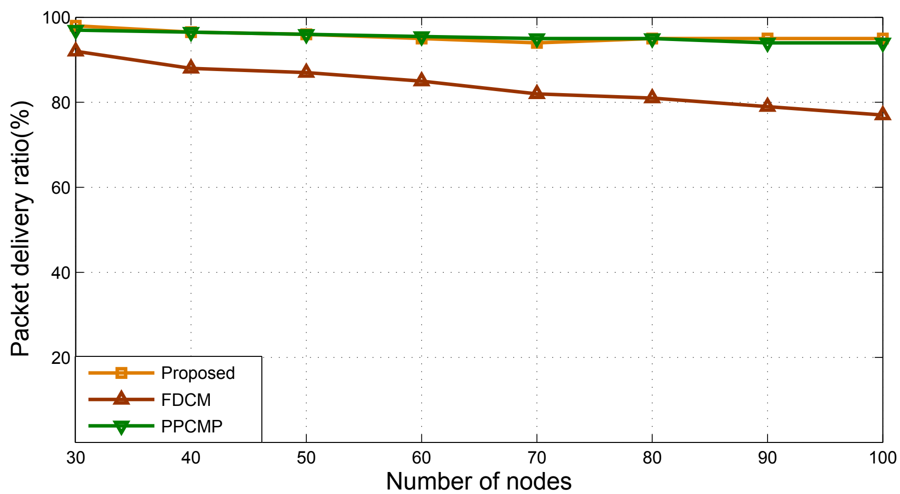


Figure 3.6: Packet Delivery Ratio.

PPCMP uses the node-disjoint multipath routing, which increases the reliability hence the delivery ratio also increases. The FDCM does not take such

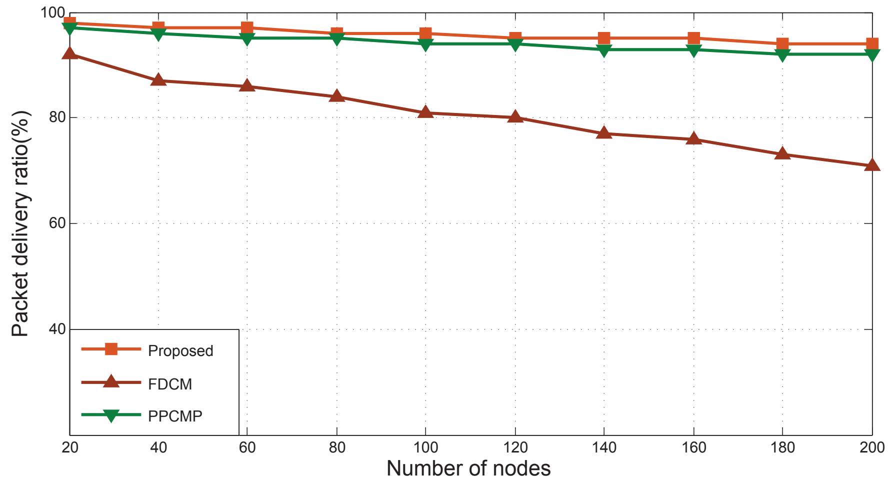


Figure 3.7: Packet Delivery Ratio (1800 sec and 200 nodes).

precautions when the path fails between the source and the sink. In fact, it chooses the neighbor cluster head from the available list without knowing the current residual energy. Hence, the reliability of the FDCM decreases. However, in the proposed scheme (CMRP), the sink itself selects the path and monitors the remaining energy of each node in the path. When it finds any node's residual energy below the threshold, it chooses another path for data transmission. Hence, the data loss is negligible.

In the Figure 3.6, it has been also observed that the proposed protocol and PPCMP gives almost the same packet delivery ratio up to 80 sensor nodes. Beyond 80 nodes the proposed protocol gives slightly better result. To further examine the performance of the proposed protocol with existing protocol the simulation has been performed with the simulation time 1800 seconds and up to 200 sensor nodes. From the result shown in Figure 3.7, it has been found that the proposed protocol behaves uniformly and gives better packet delivery ratio than the existing protocols.

3.4.5 Network Lifetime

Figure 3.8 depicts the network lifetime for various protocols. It is clearly illustrated that the network lifetime of the proposed scheme is greater than the FDCM and PPCMP. The reason behind this is, it consumes fewer control packets and balances the load among the sensor nodes.

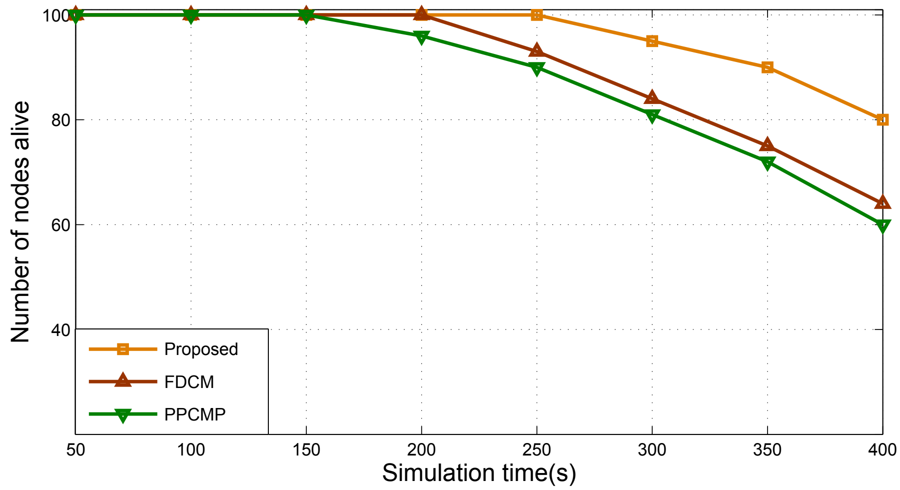


Figure 3.8: Network Lifetime.

3.5 Summary

This chapter proposed an energy-efficient routing scheme using the clustering and multipath technique called CMRP. The workload on the sensor nodes are alleviated by giving more responsibility to the base station. The multipath gives more reliability to the network, and it increases the delivery ratio and decreases the latency. In addition to that, cluster-based data collection reduces the traffic and energy consumption and also increases the lifetime of the network. The simulation result shows that the proposed protocol outperforms the existing FDCM and PPCMP protocols.

Chapter 4

Tree based Routing Protocol with Mobile Sink

Chapter 4

Tree based Routing Protocol with Mobile Sink

4.1 Introduction

In static sink environment, sensor nodes close to sink always act as the relay nodes. Relay nodes deliver the data to the sink and thus, consume more energy as compared to other nodes that are far from the sink, consequently, they die. It creates hotspots [102, 103] in the sink vicinity, and the network gets detached. Although remaining sensor nodes still have their energy and operative. Such, situation is called "crowded center effect" [60] or "energy hole/hotspot problem" [102, 103]. Sink mobility prolongs the network lifetime by diminishing the hotspot problem.

Apart from hotspot solution, the mobile sink has many advantages over the static sink such as load balancing, shorter data dissemination path and better handling of the sparse or disconnected network. Frequent change of the neighboring nodes of the sink leads to balance the load of the network. Shorter data dissemination path provides longer network lifetime by increasing throughput and decreasing energy consumption [104].

The mobile sink moves within the network and collects data from the sensor nodes. The movement of the sink may be a random, controlled or predefined and makes the network dynamic in nature. A mobile sink is required to update their location information in the network. This process consumes more energy of the network. So the routing protocols with the static sink are not suitable with the mobile sink. However, efficient broadcasting and routing technique can reduce this power consumption up to a certain extent. It is a very challenging task to manage the sink mobility and develop an efficient routing technique. This challenge motivates to develop the routing protocol with mobile sink, which uses less energy to manage the mobility of the sink.

The main flaws in the existing routing protocols with mobile sink [67, 69–71] are higher routing overhead and shorter lifetime. In this chapter, a Tree based Data Dissemination protocol with mobile sink (TEDD) is proposed to overcome the above flaws. In this protocol, any sensor node can disseminate the data to the sink via a tree. The tree is independent of the sink mobility. In the tree structure, the leaf node is known as non-relay, and the non-leaf node is called relay node. TEDD manages the mobility of the sink and balances the load among the sensor nodes to maximize the lifetime. The system model of the proposed protocol is discussed in Section 4.2. The working principle of the TEDD is presented in Section 4.3. The simulation results and analysis are explained in Section 4.4. In Section 4.5 the chapter is summarized.

4.2 System Model

4.2.1 Assumptions

The following assumptions are considered for the proposed protocol.

- Sensor nodes are all stationary after deployment.
- The sink is moving within the network.
- The sensors are randomly deployed in the network field with uniform distribution.
- The base station possesses unlimited memory, computation and battery power.
- Each node possesses its *id* and can calculate the residual energy.
- Sensor nodes are homogeneous and have the same capabilities.

- Sensor nodes have limited energy.
- Links are symmetric, i.e., the data speed or quantity is the same in both directions, averaged over time.

4.2.2 Network Model

It is considered that a wireless sensor network that consists of n number of sensor nodes and a mobile sink. The protocol generates a tree T from the sensor nodes. It can be represented as a graph $G(V, E)$ where $V = \{v_1, v_2, ...v_n\}$ is the sensor nodes and E are the links between a node set (v_i, v_j) where $v_i, v_j \in V$. The tree construction is independent of the sink position. The sink is moving within the network with the varying speed of 5 to 30 *meter/second*. The *Pause* time (δ) for sink to collect the data is 5 *seconds*. The total energy consumption by the sensor node in the network is the same as specified in Chapter 2. The sensor nodes are categorized into two types relay node and non-relay node. The relay node forwards the data from the other sensor nodes, whereas non-relay node only transmits its data to their parent relay node.

4.2.3 Mobility Model

In the simulation, to show the impact of the sink mobility, the random waypoint mobility model [105] has been considered.

- **Random Waypoint model:**

  Random Waypoint model is a "benchmark" mobility model for Ad-Hoc networks to evaluate the performance of the routing protocol. The random waypoint model is used for the sink mobility in wireless sensor networks. It randomly generates the next position in between P_{min} and P_{max}. Sink travels towards its succeeding position with constant speed or random speed. When the sink node reaches the next position, it pauses for the time duration called the *Pause* time (δ).

  The random waypoint model does not consider the previous position to calculate the next position. Hence it does not generate the relative motion.

4.3 The Proposed Protocol

The proposed protocol (TEDD) creates the tree in the network. There are two categories of the nodes in the tree: one is the relay node (RN), and the other is the non-relay node ($non - RN$). The relay node is responsible to handover the data from the nodes to its next relay node. The non-relay nodes can only communicate through a relay node. Therefore, it is a unidirectional communication. However, the communication is bi-directional between two relay nodes. The tree topology changes when the role of the node changes from a relay to non-relay or from non-relay to a relay node. To rotate the responsibility of the relay node each node's residual energy is considered.

The sink is mobile and collects the data from the source nodes through the gateway node. The gateway node may be a relay node or a non-relay node. The sink selects the gateway node based on the criteria mentioned in Section 4.3.2. The sink periodically transmits a small beacon to make the connection alive with the gateway node. If the sink moves out of the range of the current gateway node, then it selects another node as the gateway node. The rotation of the gateway node can overcome the problem of the energy hole [61]. The proposed protocol consists of various phases such as neighbor discovery, tree construction and relay node selection, and data transmission.

4.3.1 Neighbor Discovery

It is the initial phase of the proposed protocol in which each node finds its neighbor nodes. As illustrated in Algorithm 4.1 the initiator node broadcasts the `NBR_DET` packet. It includes the node id of the sender and the willingness to be the relay node with the format $<$ `NBR_DET`, $id_x, WILL_x >$. The sender nodes itself decide the willingness based on its residual energy Er. If $Er \geq E_{threshold}$, $WILL_x$ will be true otherwise false. Any node x receives the `NBR_DET` packet does the following operations:

- Checks for the existence of the sender node id, if not found, include the sender node id in the Neighbor list $Nbr(x)$.

- Checks for the willing to be a relay node, if true, then include sender node id to the candidate relay node list $CRN(x)$.

- Checks if the `NBR_DET` packet is broadcasted by the recipient node, if not, then broadcast the packet with format $<$ `NBR_DET`, $id_x, WILL_x >$ and make $NbrDETSent_x$ as true.

Neighbor discovery phase is over as soon as each node broadcast their `NBR_DET` packet. At the end, each node gets the partial view of the network in the form of neighbor information.

Algorithm 4.1 **Neighbor Discovery**

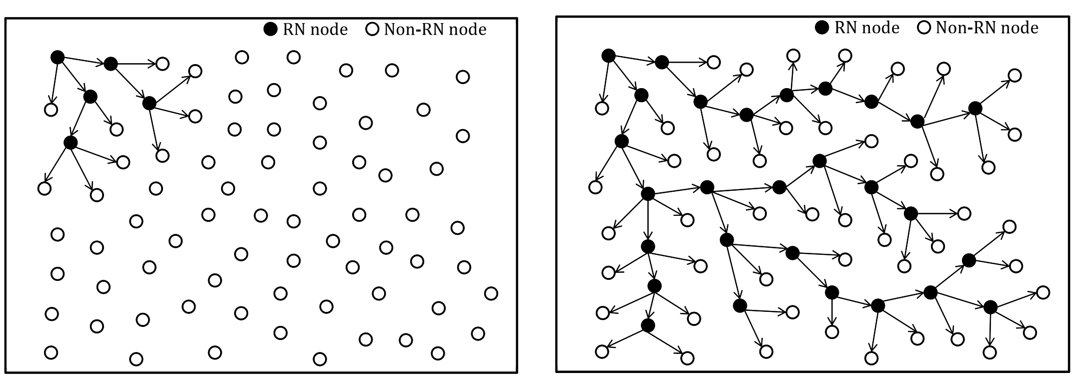
Data Structure for any sensor node x :

$Nbr(x)$: neighbor set of node x, initialized to ϕ.
$CRN(x)$: the set of neighbors of node x, which are willing to be the relay node, initialized to ϕ.
$WILL_x$: either **true** or **false** depends on the willingness of node x to become a relay node.
$NbrDETSent_x$: set to **true** when the sensor node x sends `NBR_DET` packet, initialized to **false**.

---

node x receives following packet from node y:

`NBR_DET` **:** $<$ `NBR_DET`, $id_y, WILL_y >$
if $(y \notin Nbr(x))$ **then**
    $Nbr(x) \leftarrow Nbr(x) \cup \{y\}$;
    if $(WILL_y == true)$ **then**
        $CRN(x) \leftarrow CRN(x) \cup \{y\}$;
    end if
    if $(NbrDETSent_x == false)$ **then**
        $NbrDETSent_x \leftarrow true$;
        $l\_rb($`NBR_DET`$, id_x, WILL_x)$;   ▷ Broadcast `NBR_DET` packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if



(a) Initial view of tree construction. (b) Final view of tree construction.

Figure 4.1: Tree construction steps shown in (a) and (b)

Algorithm 4.2 **Tree Construction and Relay node Selection**
Data Structure for any sensor node x :
$Children(x)$: children set of node x, initialized to ϕ.
$Parent(x)$: parent of node x, initialized to ϕ.
RN_{nodes} : set of relay nodes in the network.
$Parent\_Selected_x$: set to **true** once the sensor node x selects its parent, initialized to **false**.
$T\_MSGSent_x$: set to **true** once the sensor node x sends `T_MSG` packet, initialized to **false**.
$CRN(x)$: the set of neighbors of node x, which are willing to be the relay node, initialized to ϕ.

```
node x receives following packets from node y ∈ Nbr(x):

T_MSG : < T_MSG, id_y, Parent(y) >
if (id_x ∈ Parent(y)) then
    Children(x) ← Children(x) ∪ {id_y};
    RN_nodes ← RN_nodes ∪ {x};                    ▷ node x declare itself as a relay node
    Drop the packet;
else if (Parent_Selected_x == false && y ∈ CRN(x)) then
    Parent(x) ← y;
    Parent_Selected_x ← true;
    if ((T_MSGSent_x == false)) then
        T_MSGSent_x ← true;
        l_rb(T_MSG, id_x, Parent(x));              ▷ Broadcast T_MSG packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if

        ▷ Timeout occur to the node y when the time duration expire for the tree construction phase and
TIMEOUT_y become true.
if (TIMEOUT_y == true) then
    if (Parent_Selected_y == false) then
        l_rb(T_ERR, id_y);                         ▷ Broadcast T_ERR packet
    end if
end if

T_ERR : < T_ERR, id_y >
if (Parent_Selected_x == true) then
    T_MSGSent_x ← true;
    l_rb(T_MSG, id_x, Parent(x));                  ▷ Broadcast T_MSG packet
else
    Drop the packet;
end if
```

4.3.2 Tree Construction and Relay Node Selection

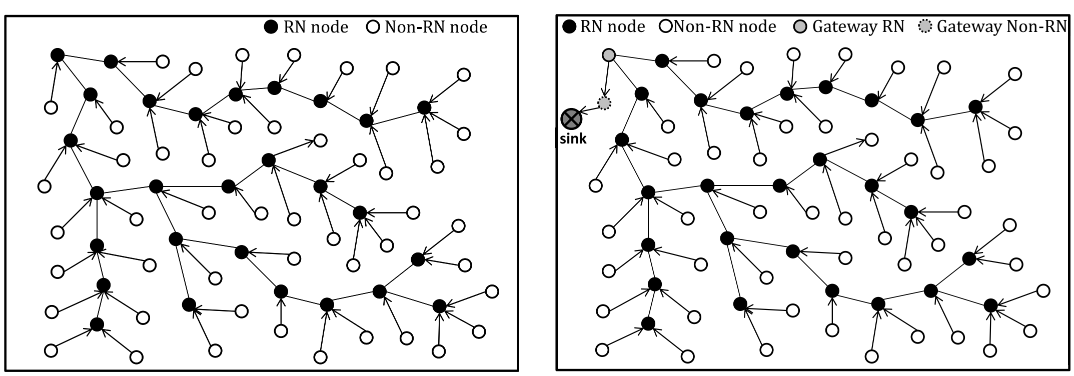
After getting the neighbor list, each node has the neighbors' information such as id and the willingness to become the relay node. The tree construction and relay node selection phase is initiated by using the neighbor information. As depicted in Algorithm 4.2, the initiator node starts the tree construction by broadcasting the `T_MSG` control packet. The node receives the following packets during the tree construction and relay node selection phase:

- `T_MSG`: In the process of tree construction `T_MSG` control packet is used. The format of the packet is $<$ `T_MSG`, $id_y, Parent(y) >$. Here id_y is the sender node id and $Parent(y)$ is its parent node id. Any node x receives the `T_MSG` packet performs following operations:

- If the sender's parent node *id* is the same as the recipient *id*, then include the sender *id* in the children list $Children(x)$ and include the recipient *id* into the relay node list RN_{nodes}.
- If it has not selected any parent, and sender belongs to the list of relay node RN_{nodes} then, select sender node as its parent.
- If $T\_MSGSent$ is false then, broadcast `T_MSG` packet with modified parameter to the network.

- `T_ERR`: Timeout occurs to the node when the time duration expires for the tree construction phase. Any node y checks for its parent node if it does not exist, then a node y broadcasts an error message `T_ERR` to its neighbor nodes. The receiver node performs following operation:
  - It initiates tree construction by broadcasting `T_MSG` if it belongs to the tree, otherwise drop the packet.

In this way, the rest of the nodes that do not belong to the tree will get an opportunity to connect with the tree as shown in Figure 4.1. At the end of tree construction, each non-relay node makes a reverse link to its parent relay node for data transmission as shown in Figure 4.2(a).



(a) Link reversal process.

(b) Sink mobility management and Gateway node selection.

Figure 4.2: Link reversal and Sink mobility management.

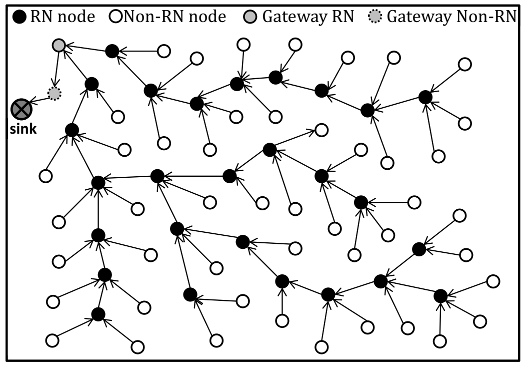


Figure 4.3: Path construction for gateway node and Data transmission.

The mobile sink moves within the network using the random waypoint mobility model. It collects the data from the sensor nodes. In TEDD, any node closest to the sink will be selected as the gateway node. If the selected gateway node is not a relay node, then it selects its parent relay node as the gateway. This process is illustrated in Figure 4.2(b). The gateway disseminates the information about the sink in the network through the relay nodes. The relay node establishes a reverse link to the relay node from where it receives the sink information as shown in Figure 4.3.

4.3.3 Data Transmission

The responsibility of the relay node is to forward the data to the next relay node. Any node can sense the data from the environment and transmits to the next relay node. Node x receives the following packet during the data transmission phase from node y as described in Algorithm 4.3.

- `DATA`: Each node in the network senses the environment, generates the data and transmits it towards the next relay node with the format $<$ `DATA`$, id_y, sec\_no_y >$. Here id_y is the id of sender node y and sec_no_y is the data sequence number of the node y. Any node that receives the `DATA` packet performs following actions:
  - If the receiver node is a relay node, and it receives any duplicate data, then it drops that data packet.

– If the receiver node is a gateway node, then forwards the data packet to the sink else forwards the `DATA` packet to its next relay node.

– Add the sender id and data sequence number to the list $Send\_Data(x)$.

Algorithm 4.3 **Data Transmission**

Data Structure for any sensor node x :

$Send\_Data(x)$: node x add the pair of id and sec_no after receiving the `DATA` packet, initialized to ϕ.

$Gateway$: node selected by the sink for data reception.

```
node x will receive following packet from node y ∈ Nbr(x):

DATA : < DATA, id_y, sec_no_y >
if (x ∈ RN_node) then
    if (< id_y, seq_no_y > ∉ Send_Date(x)) then
        if (x == Gateway) then
            Send_Data(x) ← Send_Data(x) ∪ {y, sec_no_y};
            Forward DATA packet towards the sink;
        else
            Send_Data(x) ← Send_Data(x) ∪ {y, sec_no_y};
            Forward DATA packet to its neighbor relay node towards gateway
        end if
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

Lemma 4.1. *The message complexity of the TEDD is $O(nk)$.*

Proof. Let n number of sensor nodes are deployed in the network. According to Lemma 2.2, for neighbor discovery phase message complexity of a sensor node is $O(k)$, where k is the number of neighbors and $k < n$. For the tree construction, each sensor node communicates $(1 + k)$ messages. Let 'r' number of relay nodes are used within the network, where $r < n$. The message complexity for the mobile sink management is $O(r)$ so that each node can send their data to the sink. The total message across the network is represented as $(nk + n(1 + k) + r)$. Hence, the message complexity of the TEDD protocol is $O(nk)$. □

4.4 Simulation Results

The simulation is performed for the TEDD, and the existing protocols such as probabilistic data dissemination protocol called SUPPLE [70], Multi-Point Relay based routing (SN-MPR) [71] and Adaptive Reversal Tree (ART) [67] to examine the energy consumption, end-to-end latency, data delivery ratio and network lifetime of the network as specified in Chapter 2. The performance of the proposed protocol is evaluated and compared the result with the existing tree-based protocols. For the fair comparison, the simulation parameters are equivalent to the existing protocols. The impact of the random waypoint mobility model in energy consumption is observed. The intensive set of simulation is performed using the Castalia (v3.2) simulator and based on the parameters listed in Table 4.1.

Parameter Name	**Value**
Network area	500×500 *meter*^{2}
Number of sensor nodes	200
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
δ	5 *sec*
Sink speed	(5, 10, 15, 20, 25, 30) m/sec
Mobility Model	Random Waypoint
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp_4}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{low}	0.2 nJ/sec
Simulation time	400 *sec*
MAC protocol	TMAC

Table 4.1: Simulation Parameters.

4.4.1 Average Control Packet Overhead

As observed from the Figure 4.4, that the tree reconstruction and sink management cost is very less in the proposed protocol as compared to the other protocols. In ART, the entire network should know the current position of the sink. The tree rebuilt with the nearest node to the sink as root. The tree reconstruction cost of ART depends on the affected area. However, in SN-MPR the root of the tree is the sink. Like ART, SN-MPR also rebuilt the tree when the sink moves. However, the new position of the sink only be known to the selected nodes. So the control overhead of the SN-MPR is less than the ART.

In SUPPLE, the tree is constructed, and storing nodes are selected. The storing nodes temporarily store the data from the source nodes. When the sink comes

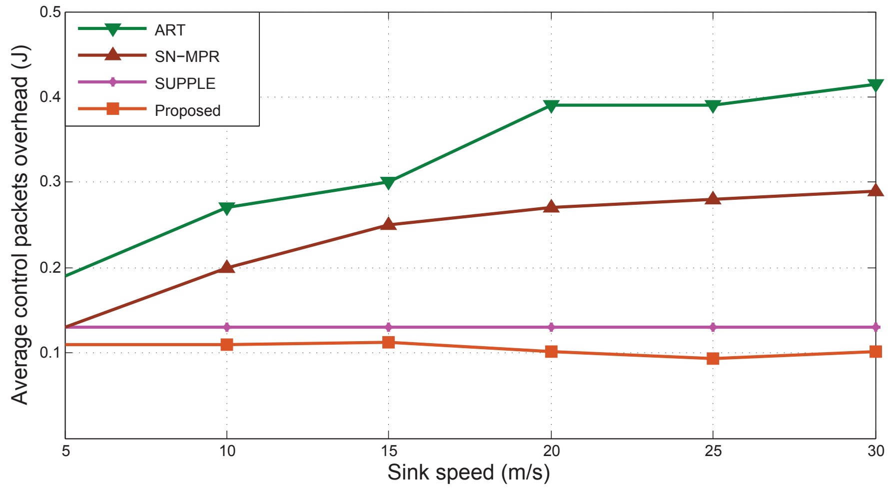


Figure 4.4: Average Control Packet Overhead.

in the range, the storing node transmits the data. Unlike the above protocols, the SUPPLE does not depend on the movement of the sink. So control packet overhead is only due to tree formation and storing node selection. However, in the proposed protocol (TEDD), the new position of the sink should be known only to the one-hop neighbors, this leads to the less control packet overhead.

4.4.2 Average Energy Consumption

The average energy consumption at each node for data and control packet is shown in the Figure 4.5. Although, in the proposed protocol, the average distance between source and sink is the same as ART and SN-MPR but due to the less control packet overhead, the proposed protocol (TEDD) outperforms the existing protocols.

In SUPPLE, the average distances between the source and the storing nodes are $n/2$, where n is the number of sensor nodes. The distance between the storing node to the sink is one-hop. Although the average distance is less, it consumes more energy than the proposed protocol. In SUPPLE, each storing node stores the data of all the sensor nodes. This enhances the traffic of the network and consequently, the energy consumption is also increasing.

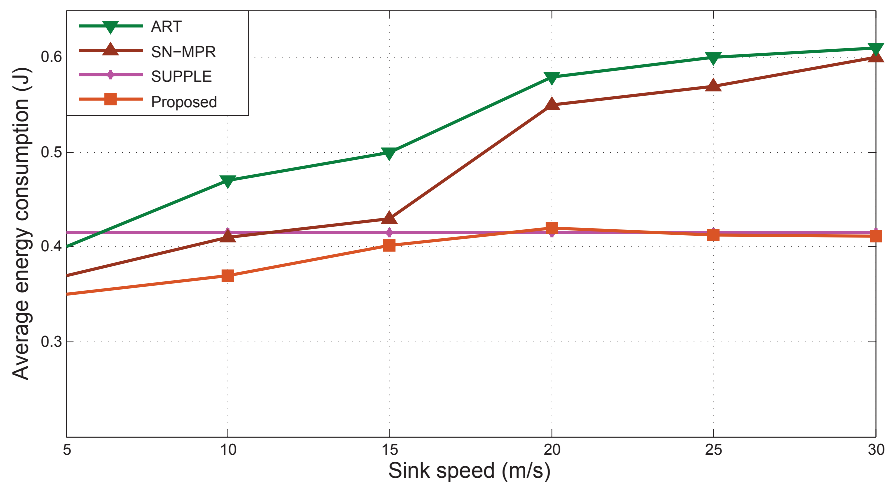


Figure 4.5: Average Energy Consumption.

4.4.3 Average End-to-End Latency

The latency mainly depends on the duration of finding the valid path between source and sink. Figure 4.6 presents the average end-to-end latency with various sink speeds using the random waypoint mobility model. The time required to reconstruct the tree based on the new position of the sink, cause the delay in ART and SN-MPR. In SN-MPR, the affected area is less than the ART. So ART causes more end-to-end latency than SN-MPR.

In SUPPLE, the sensor data is temporarily stored in the storing nodes. The storing nodes wait for the mobile sink to come within the territory. It causes more end-to-end latency than the above protocols. Whereas the proposed protocol (TEDD) takes less cost and time to manage the mobility of the sink.

4.4.4 Packet Delivery Ratio

Figure 4.7 presented the data delivery ratio with different sink speeds. SUPPLE performed well because the distance between the sink and storing node is one-hop. The result of SN-MPR is also good due to the less affected area and efficient recovery technique. The success ratio for ART decreases as the sink speeds rise. The higher sink speed increases the frequency of the link failure, which causes data loss. However, the proposed protocol is robust, i.e., the link always maintained between the source and the sink. Hence, the data delivery ratio is

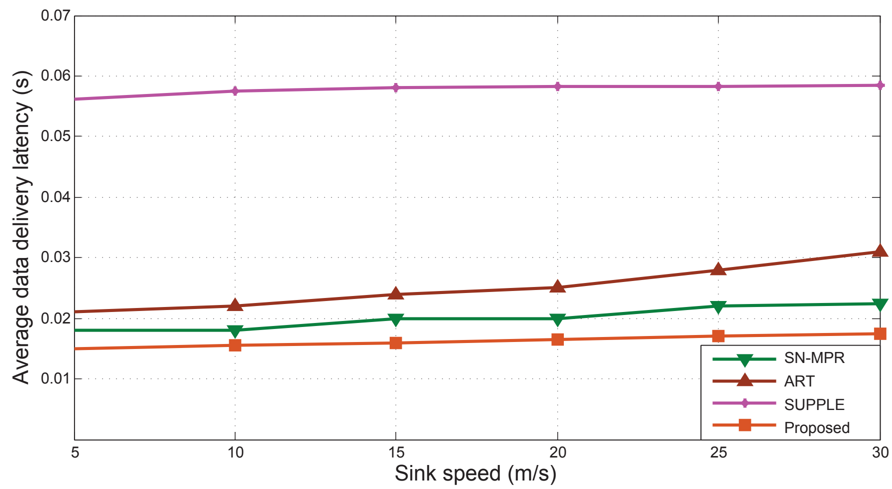


Figure 4.6: Average End-to-End Latency.

more than existing protocols.

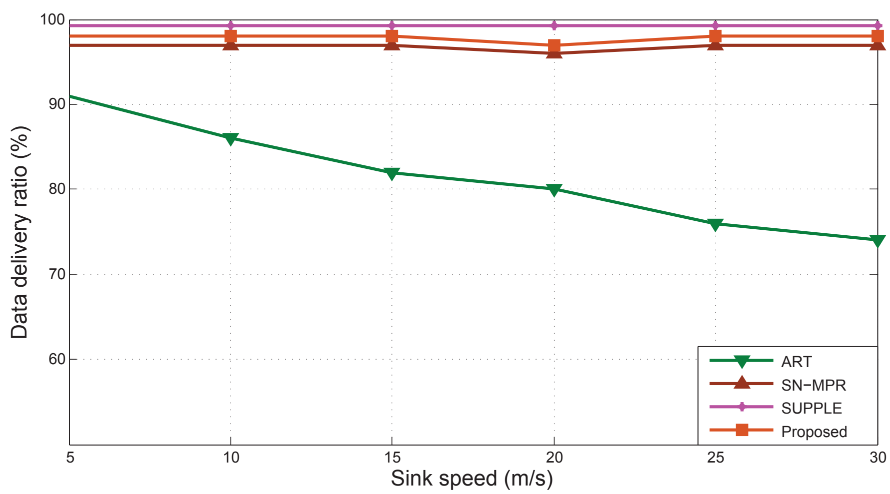


Figure 4.7: Packet Delivery Ratio.

4.4.5 Network Lifetime

In the network, the control packets are exchanged for neighbor maintenance, relay node selection, tree construction, route establishment and maintenance. It is called routing overhead and directly affects the lifetime of the network.

It has been observed from the resulting Figure 4.8 that the network lifetime of the proposed scheme (TEDD) is higher than the ART and SN-MPR and slightly better than SUPPLE. The reason behind this is, it consumes few control packets and balances the load among the sensor nodes.

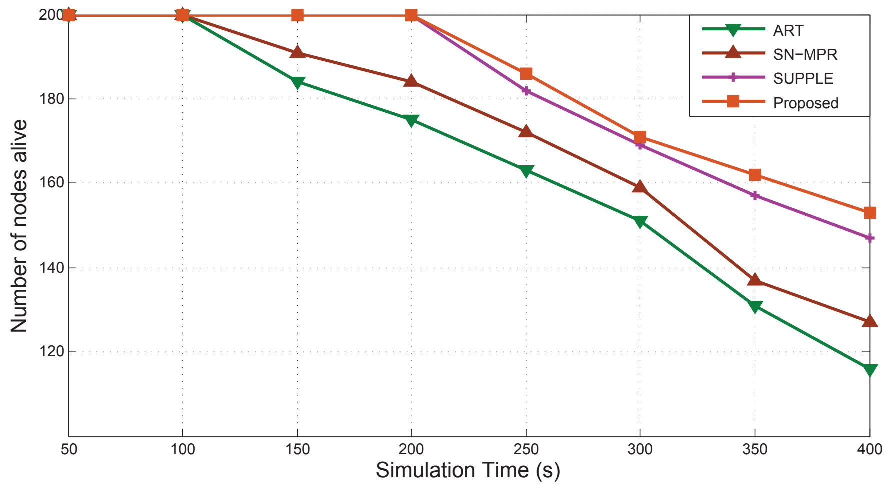


Figure 4.8: Network Lifetime.

4.5 Summary

In this chapter, a distributed tree based data dissemination protocol called TEDD has been proposed. The proposed protocol can efficiently manage the sink mobility. The simulation is performed with the random waypoint mobility model. The results are compared with the existing protocols such as SUPPLE, SN-MPR and ART. It has been observed that the TEDD outperformed the above protocols, because of its unique method to handle the sink mobility.

Chapter 5

Dense Tree based Routing Protocol with Mobile Sink

Chapter 5

Dense Tree based Routing Protocol with Mobile Sink

5.1 Introduction

The sink mobility management in a routing protocol with controlled or predictable mobility is quite easier than the random mobility. In other words, the sensor node cannot predict the next position of the sink in random mobility. A tree-based routing protocol called TEDD has been discussed in Chapter 4. TEDD with random sink mobility has been performed better than the existing tree-based protocols, but still there is some scope for improvement. The major flaws in the TEDD protocol are increased control packet overhead and path length. When the role of a relay node changes to a non-relay node then, TEDD is required to reconstruct the tree. It escalates the control packet overhead and energy consumption. The average routing path length of TEDD is greater than $n/2$, where n is the number of sensor nodes in the network. The path length directly depends on the number of relay nodes within the network.

In this chapter, a Dense Tree based Routing Protocol (DTRP) is proposed to control the overhead and reduces the path length. The tree is constructed in such a way that the number of relay node is much less than the non-relay node. Hence, the path reduces and control packet overhead also decreases. The system model of DTRP is described in Section 5.2. In Section 5.3 the working principle of the proposed protocol is presented. The simulation results and analysis are discussed in Section 5.4. In Section 5.5 the proposed protocol is summarized.

5.2 System Model

5.2.1 Network, Energy, and Mobility Model

In this chapter, the same network model and assumptions as specified in Chapter 4 have been considered. The energy model for the sensor node is the same as defined in Chapter 2. The Random Waypoint mobility model is considered for the sink mobility.

5.3 Proposed Protocol

In this chapter, an energy-efficient Dense Tree based Routing Protocol (DTRP) is proposed. In this protocol, the network is represented as a tree. Through the tree, all nodes are connected to the network. In the network, the sensor nodes create the tree independent of the sink position. The tree consists of two types of nodes; relay node and non-relay node. A relay node is the sensor node selected by another relay node. The relay node stores and forwards the data received by other sensor nodes. The non-relay node only transmits their data to the relay node. The sink node declares a relay node as the gateway node. The gateway node is the interface between the sensor network and the sink. All relay node forwards the data to the gateway node. The gateway node then transmits the received data to the sink.

After the deployment, the initiator node broadcasts the control packet for finding the one-hop neighbor node. Each node should broadcast once. In this way, each node obtains the neighbor information. After neighbor discovery, initiator node starts constructing the tree by selecting the relay node. Each non-relay node chooses the parent relay node to send the data. The links between two relay nodes are bidirectional, whereas non-relay node to relay node is unidirectional as shown in Figure 5.1. When the sink wants to collect the data, it selects a gateway node in its territory from the relay node set. Each relay node selects their neighbor relay node to transmit the data to the gateway node as illustrated in Figure 5.2(a). The proposed protocol consists of various phases such as neighbor discovery, tree construction and relay node selection, mobile sink management, data transmission, and load balancing and tree reconstruction.

5.3.1 Neighbor Discovery

In the neighbor discovery, each node finds their neighbor nodes. They maintain the list of neighbor. Each node broadcasts their willingness along with the *id* to become the relay node. The willingness is based on the residual energy of the node. So at the end of neighbor discovery phase each node consists of the neighbor list $Nbr(x)$ and candidate relay node list $CRN(x)$. All nodes have the partial information about the topology of the network. The detailed algorithm for the neighbor discovery is described in Algorithm 5.1.

Algorithm 5.1 **Neighbor Discovery**
Data Structure for any sensor node x :
$Nbr(x)$: neighbor set of node x, initialized to ϕ.
$CRN(x)$: the set of neighbors of node x, which are willing to be the relay node (candidate relay node), initialized to ϕ.
$WILL_x$: either **true** or **false** depends on the willingness of node x to become a relay node.
$NbrDETSentx$: set to **true** when the sensor node x sends `NBR_DET` packet, initialized to **false**.

```
node x receives following packet from node y:

NBR_DET : < NBR_DET, id_y, WILL_y >
if (y ∉ Nbr(x)) then
    Nbr(x) ← Nbr(x) ∪ {y};
    if (WILL_y == true) then
        RN(x) ← RN(x) ∪ {y};
    end if
    if (NbrDETSent_x == false) then
        NbrDETSent_x ← true;
        l_rb(NBR_DET, id_x, WILL_x);          ▷ Broadcast NBR_DET packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

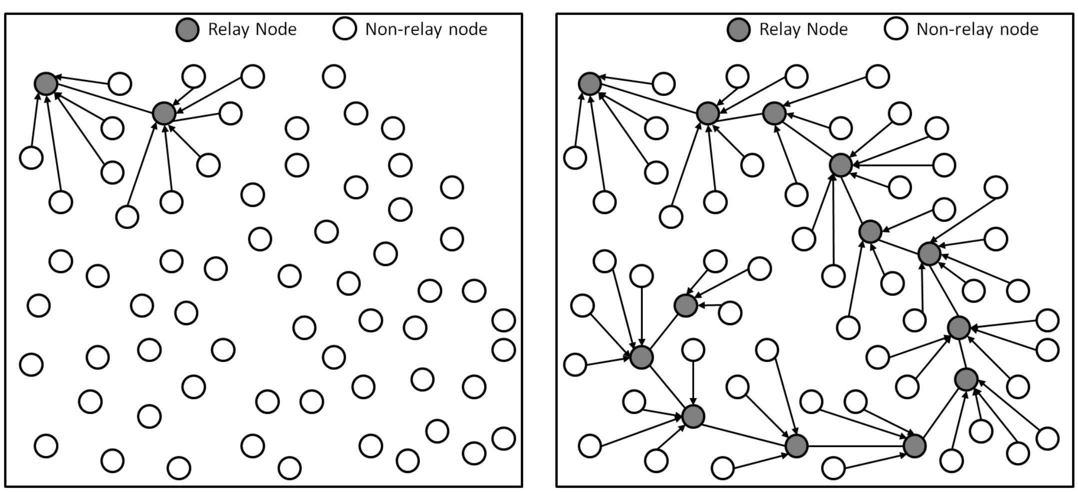
The initiator node broadcast the `NBR_DET` packet with their *id* and willingness. The node that receives the packet performs the following operations:

- Checks if the receiver node *id* is not in the neighbor list, then adds the sender *id* into the $Nbr(x)$.
- Checks if the willingness of the sender node is true, then adds the preceding node *id* into the candidate relay node list $CRN(x)$.

- The recipient node broadcasts the `NBR_DET` packet if it does not broadcast before.

5.3.2 Tree Construction and Relay Node Selection

In the tree construction and relay node selection phase, the initiator node selects the first candidate relay node as the relay node and deletes that node from the candidate relay node list. It creates a `T_MSG` packet with its *id* and selected relay node *id* and broadcast it. The receiver node selects the sender *id* as parent and next node for data transmission if not selected any parent previously as shown in Figure 5.1(a). If the receiver node is the chosen relay node by the sender relay node, then the receiver node deletes the sender *id* from the candidate relay node list and changes its status from Non-RN node to RN node. Again, receiver node selects the relay node from the candidate relay node list and broadcast the `T_MSG` packet to create the tree in the network. Each node has its parent node and next relay node for data transmission as illustrated in Figure 5.1(b). If any node is not connected with the tree, then it generates an error message `ERR` and broadcasts it. If it receives the `T_MSG` in response from the relay node, it joins the network by selecting the parent and next relay node.



(a) Initial view of tree construction. (b) Final view of tree construction.

Figure 5.1: Tree construction steps shown in (a) and (b).

At the end of tree construction and relay node selection phase, each node becomes the part of the tree. The relay node has an additional responsibility to forward the data from the neighbor nodes (relay or non-relay nodes). The non-relay node only transmits their data to the parent relay node. The Algorithm 5.2 presented the tree construction and relay node selection.

Algorithm 5.2 **Tree Construction and Relay node Selection**

Data Structure for any sensor node x :

$Nbr(x)$: neighbor set of node x.
$Parent_x$: parent of node x.
RN_x : relay node selected by the node x.
$Parent\_Selected_x$: set to **true** once the sensor node x selects its parent, initialized to **false**.
$CRN(x)$: the set of neighbors of node x, which are willing to be the relay node (candidate relay node).
$TreeConstruction_x$: set to **true** once the sensor node x called the $TreeConstruction()$, initialized to **false**.
$next\_node_x$: the relay node x selects the next relay node for data transmission.
$Status_x$: set to ***RN***, when the sensor node x has been selected as relay node, initialized to ***non-RN***.

```
procedure TreeConstruction()
    RN_x ← CRN(x_0);
    CRN(x) ← CRN(x) − CRN(x_0);
    l_rb(T_MSG, id_x, RN_x);                                    ▷ Broadcast T_MSG packet
end procedure

node x receives following packets from node y ∈ Nbr(x):

T_MSG : < T_MSG, id_y, RN_y >
if (Parent_Selected_x == false) then
    Parent_x ← id_y;
    next_node_x ← id_y;
    Parent_Selected_x ← true;
    if (id_x == RN_y) then
        CRN(x) ← CRN(x) − CRN(x_{id_y});
        Status_x ← RN;
        if (TreeConstruction_x == false) then
            TreeConstruction_x ← true;
            TreeConstruction();
        end if
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if

        ▷ Timeout occur to any node x when the time duration expires for the tree construction phase and
TIMEOUT_y become true.
if (TIMEOUT_x == true) then
    if (Parent_Selected_x == false) then
        l_rb(T_ERR, id_x);                                      ▷ Broadcast T_ERR packet
    end if
end if

node x receives following packets from node y ∈ Nbr(x):

T_ERR : < T_ERR, id_y >
if (Status_x == RN)  then
    l_rb(T_MSG, id_x, RN_x);                                    ▷ Broadcast T_MSG packet
else
    Drop the packet;
end if
```

In the algorithm, a procedure is defined called $TreeConstruction()$. It selects the relay node from the candidate relay node list, updates the candidate relay node list $CRN(x)$ and broadcasts the `T_MSG` for the tree construction. The node that receives the `T_MSG` packet does the following operations:

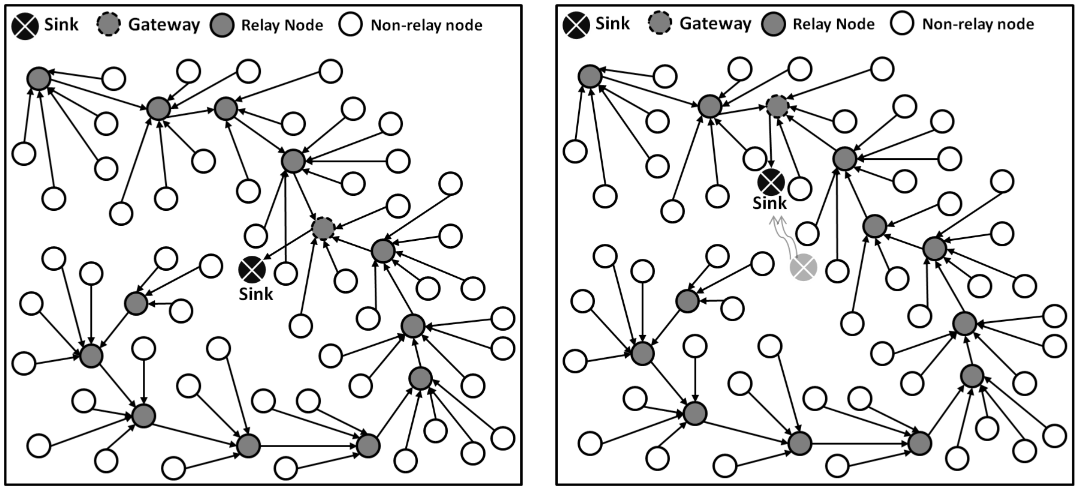
- Check if not it is selected the parent, then select sender node as the parent and $next\_node_x$.
- Check if the receiver node is the relay node selected by the sender node, then it updates the candidate relay node list.
- Updates the status to relay node (RN) and call the $TreeConstruction()$ procedure.

At the end of this phase when the timeout occurs for each node the algorithm checks for the node that does not select any parent. That node generates an error message `ERR` and broadcasts. If any relay node receives the `ERR` packet, it replies with `T_MSG` packet.

5.3.3 Mobile Sink Management

The sink is moving within the network. The random waypoint model for the sink mobility has been considered. The mobile sink has been considered to reduce the effect of energy hole problem [61]. The mobile sink moves within the network and collects the data from the nodes through the gateway node as shown in Figure 5.2. The gateway works as an interface between the sensor network and the sink. The sink chooses one of the relay nodes in its territory as a gateway node. The gateway node broadcasts an acknowledgment (`ACK`) packet in the network. The relay node selects their next relay node ($next\_node_x$) to send the data towards the sink. The sink sends a `STOP` signal to the gateway node to halt the data transmission just before it moves to the new position.

The detail description of the mobile sink management is discussed in Algorithm 5.3. When the mobile sink reaches to the new position, it broadcast a beacon packet. The `Beacon` packet consists of sink *id*. The relay node that receives the beacon should reply the sink with `BeaconRelay` packet. The `BeaconReply` packet consists of its *id* and the sink *id*. When the sink receives first `BeaconReply` packet,



(a) Gateway node selection and Data transmission.

(b) Sink mobility management.

Figure 5.2: Gateway selection and Data transmission and Sink mobility management.

it selects the sender relay node as the gateway and sends a `Gateway` packet. The gateway packet consists of sink *id* and selected gateway node *id*. When the selected gateway node receives the packet, it selects a next node as sink *id* and broadcasts the acknowledgment (`ACK`) packet. The `ACK` packet consists of the sender *id* and gateway node *id*. The recipient relay node performs the following operations:

- Checks if the `ACK` packet is not for the previous gateway node, then
- Selects the gateway node as newly selected gateway node and selects the *next_node* as sender node *id*.
- Forwards the `ACK` packet with its *id* and gateway node *id*.

In this way, each relay node selects the next relay node to transfer the data. When the sink moves from its position, it sent a `STOP` signal to the gateway node. The gateway node forwards the `STOP` signal to the network. So that the data loss will decrease, and the delivery ratio will increase.

5.3.4 Data Transmission

When the relay node's *SendData* flag is true, it can immediately start the data transmission to the next relay node. The non-relay node can send their data

Algorithm 5.3 **Mobile Sink Management**

Data Structure for any sensor node x and sink:
$Gateway_{sink}$: gateway node selected by the sink.
$next\_node_x$: the relay node x selects the next relay node for data transmission.
$Status_x$: set to ***RN*** once the sensor node x selected as relay node, initialized to ***non-RN***.
$SendData_x$: set to **true** once the relay node chooses the $next\_node_x$ for data transmission, initialized to **false**.
$Gateway_x$: gateway node selected by the node x.

```
node x receives following packets from the sink:

Beacon: < Beacon, id_sink >
if (Status_x == RN) then
    l_rf(BeaconReply, id_x, id_sink);        ▷ Unicast the BeaconReply packet to the sink.
end if

the sink receives following packets from node y:

BeaconReply: < BeaconReply, id_y, id_sink >
Gateway_sink ← id_y;
l_rf(Gateway, id_sink, Gateway_sink);   ▷ the sink unicasts the Gateway packet to the selected gateway node.

node x receives following packets from the sink:

Gateway: < Gateway, id_sink, Gateway_sink >
if (id_x == Gateway_sink) then
    next_node_x ← id_sink;
    l_rb(ACK, id_x, Gateway_sink);            ▷ Boradcast the ACK packet.
else
    Drop the packet;
end if

node x receives following packets from the relay node y:

ACK: < ACK, id_y, Gateway_sink >
if (Status_x == RN) then
    if (Gateway_x ≠ Gateway_sink) then
        Gateway_x ← Gateway_sink;
        SendData_x ← true;
        next_node_x ← id_y;
        l_rb(ACK, id_x, Gateway_sink);        ▷ Boradcast the ACK packet.
    end if
else
    Drop the packet;
end if
```

when they select the next relay node. Once the data packet reaches the gateway node, it forwards the packet to the sink.

The detail description is presented in Algorithm 5.4. The receiver node performs the following operations:

- Checks if the recipient node is the same as the *next_node id*, then
- Checks if it receives the new data, then
- Adds the source *id* and sequence number in the *SendData* list and
- If the *SendData* flag is true, then forwards the data to its next relay node.

Algorithm 5.4 **Data Transmission**

Data Structure for any sensor node x :

$SendData_x$: set to **true** once the relay node chooses the $next\_node_x$ for data transmission, initialized to **false**.
$Send\_Data(x)$: node x add the pair of id and sec_no after receiving the `DATA` packet, initialized to ϕ.

```
node x will receive following packet from node y ∈ Nbr(x):

DATA : < DATA, id_source, sec_no_source, next_node_y >
if (id_x == next_node_y) then
    if (< id_source, sec_no_source > ∉ Send_Date(x)) then
        Send_Data(x) ← Send_Data(x) ∪ {id_source, sec_no_source};
        if (SendData_x == true) then
            l_rf(DATA, id_source, sec_no_source, next_node_x);      ▷ forward the DATA packet to the next node.
        end if
    end if
else
    Drop the packet;
end if
```

Lemma 5.1. *The message complexity of the DTRP is $O(nk)$.*

Proof. The message complexity for neighbor discovery and mobile sink management is similar to TEDD as described in Lemma 4.1. In this protocol, for the tree construction, each node receives one message, and each relay node broadcasts one message. Therefore, the total message across the network is represented as $(nk+n+r+r)$ and the message complexity for DTRP is $O(nk)$. □

5.3.5 Load Balancing and Tree Reconstruction

In this section, the method to balance the load among the nodes in the network is presented. So the lifetime of the network may increase. There are two types of nodes in the network relay node and non-relay node. The relay node has the extra responsibility to forwards the data from other nodes towards the sink. Whereas non-relay nodes only transmit their data to the parent relay node. So the energy consumption is less in case of the non-relay node. If the residual energy of any relay node is less than the threshold value, then the load balancing technique handles the situation by giving relay node's responsibility to another non-relay node. Hence, the load may evenly be distributed among the nodes in the network.

If it is needed to change the relay node, then the tree reconstruction is required in the network. So the algorithm is designed in such a way that the cost to reconstruct the tree is less, and it affects only the limited area of the network. The detail description of load balancing and tree reconstruction is shown in the Algorithm 5.5.

Algorithm 5.5 **Load Balancing and Tree Reconstruction**
Data Structure for any sensor node x :
$Nbr(x)$: neighbor set of node x.
$Parent_x$: parent of node x, initialized to ϕ.
RN_x : relay node selected by the node x .
Er_x : residual energy of any node x .
$Parent\_Selected_x$: set to **true**, once the sensor node x selects its parent, initialized to **false**.
$CRN(x)$: the set of neighbors of node x, which are willing to be the relay node (candidate relay node).
$Status_x$: set to ***RN***, once the sensor node x has been selected as relay node, initialized to ***non-RN***.
$RNfound$: set to **true** once the sensor node got the desired relay node, initialized to **false**.

```
if (Status_x == RN && Er_x ≤ E_threshold) then
    l_rb(LB, id_x, RN_x);                                  ▷ Broadcast LB packet.
end if

node x receives following packets from node y ∈ Nbr(x):

LB: < LB, id_y, RN_y >
if (Parent_x == id_y) then
    Parent_Selected_x ← false;
    if (id_x == RN_y) then
        l_rb(LBReply, Nbr(x), id_x, Parent_x);             ▷ Unicast the LBReply packet to its parent.
    end if
else
    Drop the packet;
end if

node x receives following packets from node y ∈ Nbr(x):

LBReply: < LBReply, Nbr(y), id_y, Parent_y >
if (id_x == Parent_y) then
    l_rb(NBR_LIST, Nbr(RN_x), id_x, Parent_x);             ▷ Unicast the NBR_LIST packet to its parent.
end if

node x receives following packets from node y ∈ Nbr(x):

NBR_LIST: < NBR_LIST, Nbr(RN_y), id_y, Parent_y >
if (id_x == Parent_y) then
    for i ← 1, n do                                        ▷ n is the number of candidate relay node
        if (CRN(x[i]) ∈ Nbr(RN_y)) then
            RN_x ← CRN(x[i]);
            RNfound ← true;
            CRN(x) ← CRN(x) − CRN(x[i]);
            l_rb(PT_MSG, id_x, RN_x, RN_y);                ▷ Unicast the PT_MSG packet to the relay node.
        end if
    end for
    if (RNfound == false) then
        TreeConstruction();
    end if
else
    Drop the packet;
end if

node x receives following packets from node y ∈ Nbr(x):

PT_MSG: < PT_MSG, id_y, RN_y, RN_z >
if (id_x == RN_y) then
    RN_x ← RN_z;
    CRN(x) ← CRN(x) − CRN(x[RN_z]);
    l_rb(PT_MSG, id_x, RN_x, RN_y);                        ▷ Broadcast the PT_MSG packet.
else
    Drop the packet;
end if
```

If the residual energy of any relay node goes beyond the threshold value, then it broadcasts a load balance packet LB. The LB packet consists of the *id* and the selected relay node. The node that receives the LB packet performs the following operations:

- Checks if the parent of the receiver node is the same as the sender node, then it makes *parent_selected* as false.
- Checks if the *id* of the receiver node is the same as the selected relay node then it replies with `LBReply` packet.

The `LBReply` packet consists of the *id*, neighbor information and parent node *id*. The receiver node performs the following operation:

- Checks if its *id* is the same as the parent node *id*, then it generates a `NBR_LIST` packet for the parent relay node.

The `NBR_LIST` packet consists of *id*, the neighbor information of the relay node and parent node *id*. The receiver node performs the following operations:

- Checks if its *id* is the same as the parent node *id*, then
- Checks if any candidate relay node belongs to the neighbor list of the received neighbor list, then
- Select the relay node that belongs to the received neighbor list and broadcast the `PT_MSG`.
- If the relay node was not found, then the $TreeConstruction()$ procedure is called to reconstruct the tree.

The `PT_MSG` packet consists of *id*, selected relay node and the relay node of the previous relay node. The receiver node performs the following operations:

- Checks if its *id* is the same as the selected relay node *id*, then
- Select the relay node as the same as the relay node chosen by the previous relay node and broadcast the `T_MSG`.

To reduce the overhead of tree reconstruction, a new relay node is detected that affects only two hop neighbors. This phase is important to increase the lifetime of the network and reduces the energy consumption.

5.4 Simulation Results

Through the simulation, the proposed protocol (DTRP) performance has been analyzed and compared with the existing protocols such as SN-MPR [71] and TEDD. Each experiment has been performed with the varying sink speed from $5\,meter/second$ to $30\,meter/seccond$. The impact of the sink speed in energy consumption, end-to-end delay, delivery ratio and network lifetime has been observed. The intensive set of simulation is performed using the Castalia (v3.2) simulator and based on the parameters listed in Table 5.1.

Parameter Name	**Value**
Network area	$500 \times 500\ meter^2$
Number of sensor nodes	200
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
δ	5 *sec*
Sink speed	(5, 10, 15, 20, 25, 30) m/sec
Mobility Model	Random Waypoint
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{low}	0.2 $nJ/second$
Simulation time	400 *sec*
MAC protocol	TMAC

Table 5.1: Simulation Parameters.

5.4.1 Average Control Packet Overhead

Figure 5.3 illustrated the average energy consumption of control packet with varying sink speed. The sensor nodes transmit the control packets to construct a tree and manage the sink mobility. The tree reconstruction and sink management cost is very less in the proposed protocol (DTRP) as compared to the other protocols. In SN-MPR [71], the root of the tree is the sink. It rebuilt the tree when the sink moves, which leads to more control packet overhead. In TEDD, the tree structure does not depend on the sink position. However, it rebuilt the tree as the new relay node selected. In the proposed protocol, the selection of the new relay node only affects the two-hop neighbors. In DTRP, the number of the relay node is less than the TEDD, which also reduces the control packet overhead.

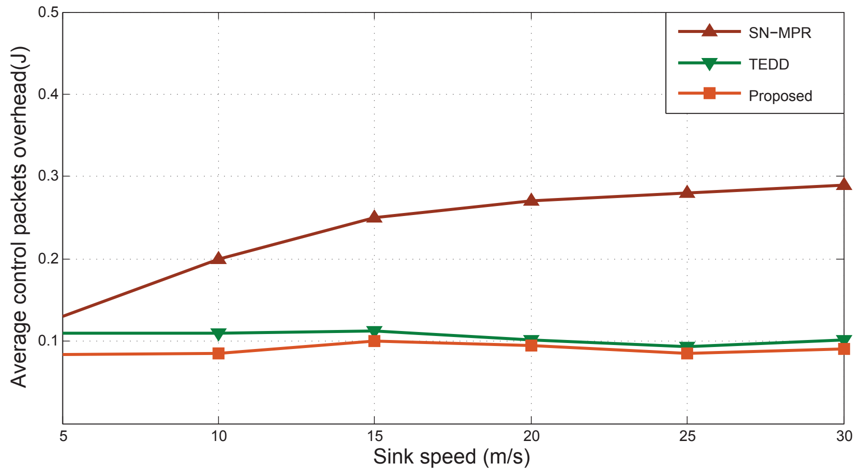


Figure 5.3: Control Packet Overhead.

5.4.2 Average Energy Consumption

The total energy consumption at each node for data and control packet is shown in the Figure 5.4. In the proposed protocol (DTRP), the average distance between a source and the sink is less than SN-MPR and TEDD. Additionally, the less control packet overhead of the proposed protocol also decreases the energy consumption.

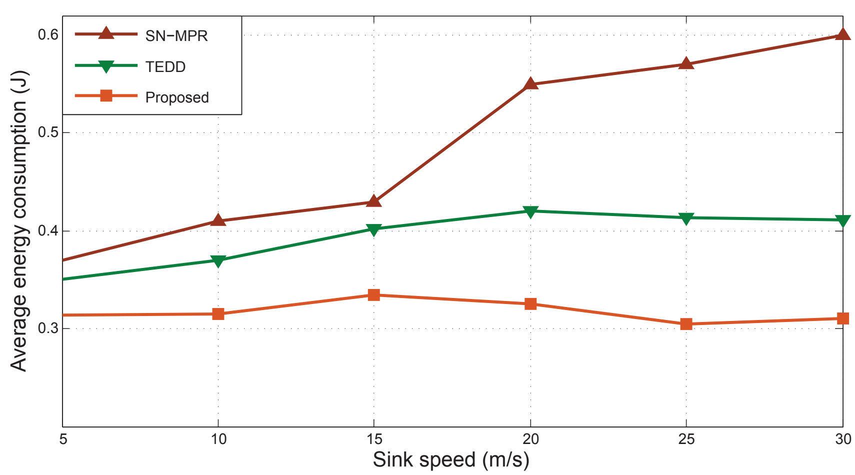


Figure 5.4: Average Energy Consumption.

5.4.3 Average End-to-End Latency

It depends on the time duration to find the valid path and propagate the data to the sink. Figure 5.5 presents the average end-to-end delay with various sink speeds. The time required to reconstruct the tree based on the new position of the sink causes the delay in SN-MPR. The proposed protocol (DTRP) takes less cost and time to manage the mobility of the sink than TEDD. As it can be seen from the Figure 5.5 that the proposed protocol outperforms the above mentioned protocols in terms of average latency.

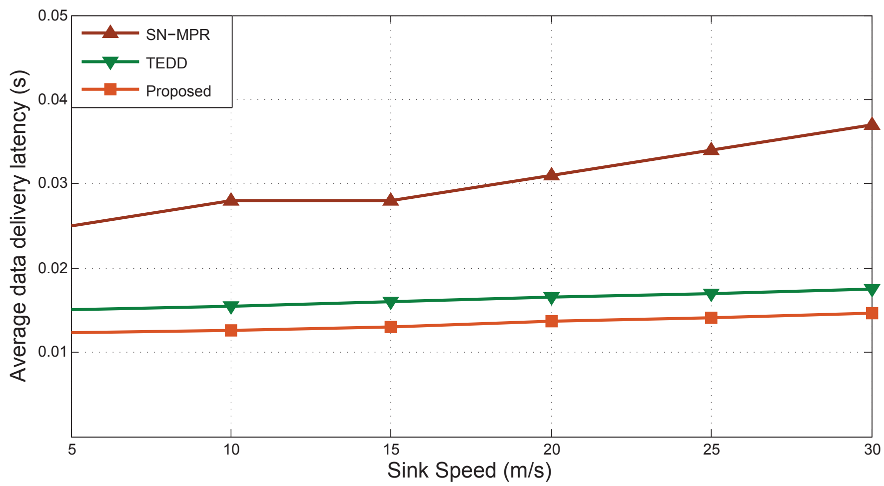


Figure 5.5: Average End-to-End Latency.

5.4.4 Packet Delivery Ratio

Figure 5.6 shows the packet delivery ratio with respect to different sink speeds.

Packet delivery ratio represents the success rate of the data delivery. The higher sink speed increases the frequency of link failure, which causes data loss. However, the proposed protocol (DTRP) and TEDD are robust, i.e., the link always maintained between the source and the sink. Hence, the packet delivery ratio of the DTRP and TEDD is better that SN-MPR.

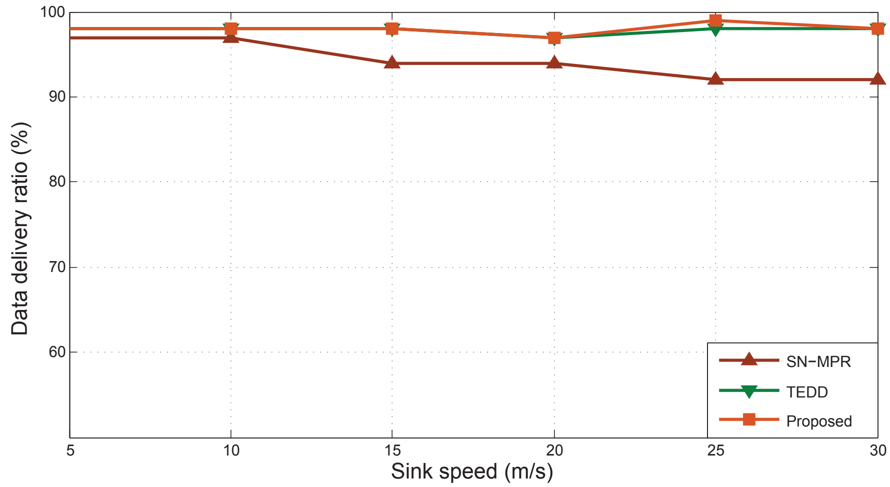


Figure 5.6: Packet Delivery Ratio.

5.4.5 Network Lifetime

It is the time span of the network when the first node dies. In the network, the control packets are exchanged for neighbor maintenance, relay node selection, tree construction, route establishment and maintenance. It increases the routing overhead and directly affects the lifetime of the network.

It is clearly shown in Figure 5.7 that, the network lifetime of the proposed scheme (DTRP) is greater than the TEDD and SN-MPR. The reason behind this is, it consumes less control packets and balances the load among the sensor nodes.

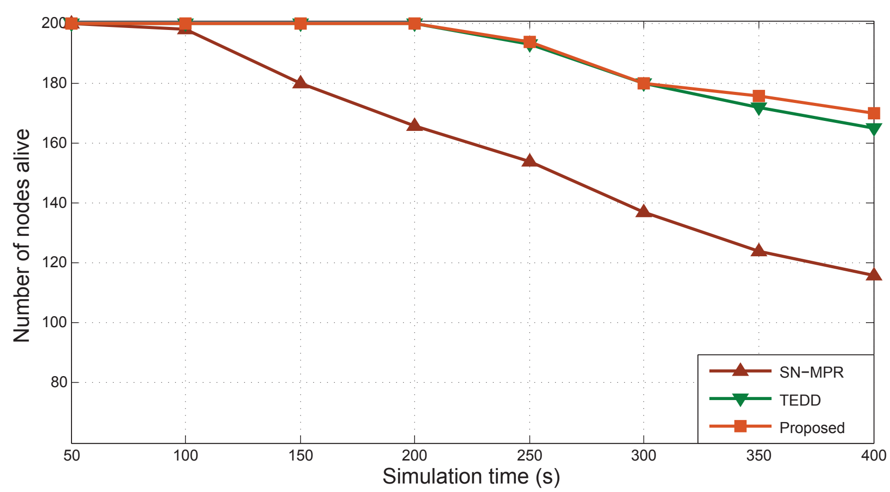


Figure 5.7: Network Lifetime.

5.5 Summary

In this chapter, a robust and efficient dense tree based routing protocol (DTRP) has been proposed. The proposed protocol can effectively balance the load among the sensor nodes and manage the sink mobility. The proposed protocol has been simulated and compared with the existing protocols such as SN-MPR and TEDD. It has been observed that the proposed protocol outperformed the above protocols.

Chapter 6

Clustered Tree based Routing Protocol with Mobile Sink

Chapter 6

Clustered Tree based Routing Protocol with Mobile Sink

6.1 Introduction

The previously proposed tree-based protocols TEDD and DTRP manage the sink mobility. In DTRP, the average path length is less as compared to TEDD. However, in large-scale WSN environment, both protocols suffer from the redundant data transmission. In TEDD and DTRP, the relay node forwards the data from other sensor nodes. Relay nodes in such an environment waste their energy in transferring the redundant data. Hence, it is required to eliminate the redundancy in the adequate level, to conserve energy. Data aggregation is a technique in which each relay node can aggregate the data, process them and transmit a single packet.

DTRP contains a lesser relay node than TEDD, but both cannot restrict the number of relay nodes in the network. As relay nodes have more responsibility than the non-relay nodes, it consumes more energy. If any technique can restrict the number of relay nodes, then it can be possible to reduce the energy consumption. This issue motivates to develop a routing protocol that can aggregate the data and restrict the number of relay nodes in the network.

In this chapter, a Clustered Tree based Routing Protocol (CTRP) is developed. In the CTRP, the network is divided into virtual grids, and clusters are formed in each grid with a cluster head. The cluster head is selected based on its residual energy and the distance from the centroid of the grid. Once a cluster head is selected, a tree is formed using these cluster heads, i.e., all cluster heads are treated as the vertices of the tree. Cluster heads aggregate the data and transmit it to the sink via this tree. The number of cluster heads is restricted to the number of grids present in the network. Further, the sink management method can efficiently handle the sink mobility. The proposed load balancing method balances the load among the sensor nodes to enhance the lifetime of the network. The system model of the proposed protocol is described in Section 6.2. The algorithm and detail description of the proposed protocol is presented in Section 6.3. In Section 6.4 the simulation parameter, results and analysis are discussed. Finally, the chapter is summarized in Section 6.5.

6.2 System Model

6.2.1 Network Model

The network can be presented as the graph $G(V, E)$, where $V = \{v_1, v_2, ...v_n\}$ is the set of sensor nodes in the network. Each sensor node has the maximum communication range of radius R and E is the edge (link) between the node set (v_i, v_j), where $v_i, v_j \in V$. The sensor nodes are static, and a sink is moving within the network with the speed varying from 5 to 30 *meter/second*. A pause time (δ) is considered for the sink to collect the data. Besides, the assumptions taken in Chapter 4 the following assumptions are considered such as the sensor node knows their location information, and the node can vary their transmission range up to the maximum range R. Also, the network is divided into equal sized virtual grids. The grids are formed in such a way that every node of a grid can communicate directly with the nodes of adjacent and diagonal grids. The same energy model as described in the Chapter 3 has been considered for the sensor nodes. The Random Waypoint mobility model has been taken for the sink mobility.

6.3 The Proposed Protocol

The proposed protocol is a clustered tree based routing protocol. This approach is the combinations of two schemes; one is a cluster formation in the entire network, and the other is the tree formation over the clusters. In the protocol, the entire network is virtually divided into equal-sized grids, and clusters are formed within each grid. The cluster formation procedure includes cluster head election and joining process between the cluster head and its corresponding cluster members. After the cluster formation, the cluster heads are treated as vertices for tree formation. For load balancing, cluster head is re-elected only when the cluster head losses their energy below to the threshold value. The proposed protocol consists of five phases such as grid construction, cluster formation, tree construction, sink management, data transmission and load balancing.

6.3.1 Grid Construction

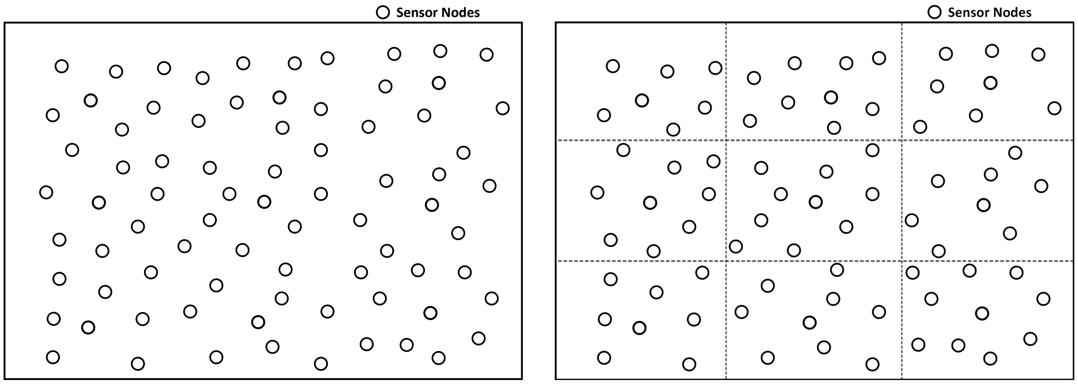
The grid formation with the assistance of location finding techniques [26,27] or GPS [25] are very simple. The cluster establishment in equally sized square grids takes very less control overhead. In the early grid formation techniques [45, 106], the grid size $S_g \leq \frac{R}{\sqrt{5}}$, has been chosen to communicate with the adjacent grid, i.e., horizontal and vertical only. Where S_g is the grid size, and R is the communication range of the sensor node. In the recent work [107, 108], it has been found that the nodes in diagonal grids can communicate with the grid size $S_g \leq \frac{R}{\sqrt{8}}$. This smaller-sized grid provides better connectivity with neighbor grids and freedom to transmit the data with shorter path length. To construct the grids, once the grid size is decided, the sensor node finds their grid coordinates (X, Y) in which they belong. The coordinates can be calculated based on the node's location (x, y) as:

$$X = \left\lceil \frac{x}{S_g} \right\rceil ; Y = \left\lceil \frac{y}{S_g} \right\rceil ; \tag{6.1}$$

Each node can calculate their grid coordinate using the Equation (6.1). Finally the entire network is divided into equal sized grids or cells as shown in Figure 6.1(b).

6.3.2 Cluster Formation

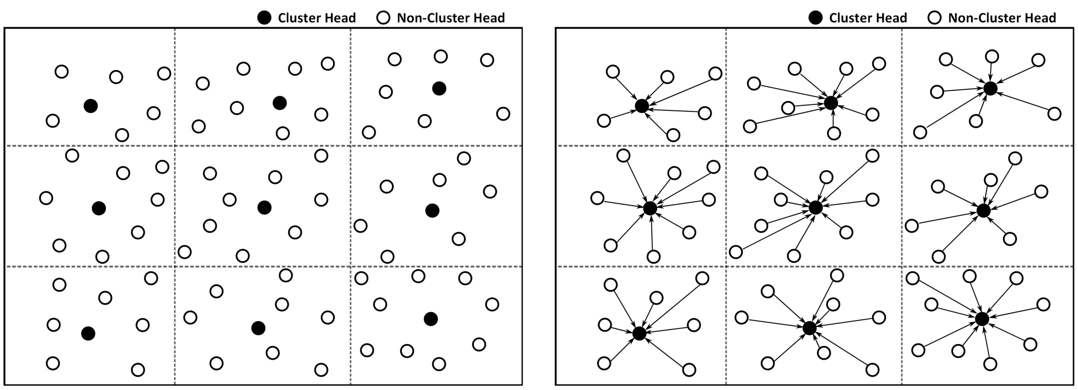
Cluster formation phase is initiated after the grid construction phase in which the clusters are formed. Cluster head and non-cluster head nodes are two different



(a) Initial view of the network. (b) Final view of grid construction.

Figure 6.1: Grid Construction.

categories of sensor nodes, which are represented in Figure 6.2(a) by filled and unfilled bubbles respectively.



(a) Cluster Head selection. (b) Final view of cluster formation.

Figure 6.2: Cluster Head selection and Cluster formation.

The cluster formation starts with the selection of a cluster head. To select the cluster head the proposed protocol ensures the following criteria:

- The residual energy of the sensor node should be greater than threshold,

  Let G_z the coordinate of any grid,

  $CH(z)$ is the cluster head of any grid G_z, and

  $Er(z)$ is the residual energy of any node $z \in G_z$, then

  $Er(z) \geq E_{threshold}$ $\triangleright$ This is the first criteria for cluster head selection

- and the sensor node should close to the centroid of the grid.

Let z_1, z_2, z_3, ...z_j are the nodes belong to the grid G_z.

and $\mid D(z_i) \mid$ is the distance of any node z_i from the centroid of the grid.

So, $CH(z) = \min_{1 \leq i \leq j}(\mid D(z_i) \mid)$ ▷ This is the second criteria for cluster head selection

When the cluster heads are selected from each grid, they broadcast advertisement (`CH_ADV`) within the grid. The non-cluster head nodes join (`CH_JOIN`) the cluster head of the same grid and create the cluster as shown in Figure 6.2(b). The cluster head generates the time-slot schedule for cluster members to collect the data in the collision-free manner. The cluster formation process is illustrated in Algorithm 6.1.

Algorithm 6.1 **Cluster Formation**
Data Structure for any sensor node x :
$CH(x)$: cluster head of node x, initialized to ϕ.
G_x: Grid coordinate of node x.
$CHSelected_x$: set to **true** when the sensor node x selected the cluster head, initialized to **false**.
$ChMbr(x)$: set of cluster members of any cluster head x, initialized to ϕ.

node x receives following packet from node y: where $x \notin CH$ & $y \in CH$

```
CH_ADV : < CH_ADV, id_y, G_y >;
if (G_x == G_y) then
    CHSelected_x ← true;
    id_CH(x) = id_y;
    l_rf(CH_JOIN, id_x, id_CH(x));          ▷ Send the join request to the cluster head
else
    Drop the packet;
end if
```

node x receives following packet from node y: where $x \in CH$ & $y \notin CH$

```
CH_JOIN : < CH_JOIN, id_y, id_CH(y) >
if (id_x == id_CH(y)) then
    ChMbr(x) ← ChMbr(x) ∪ y;
    After receiving all CH_JOIN, cluster head node x broadcast the time-slot schedule to the cluster members
ChMbr(x).
else
    Drop the packet;
end if
```

6.3.3 Tree Construction

In this phase, the tree is constructed with cluster heads as vertices of the tree. Any cluster head that initiates the tree construction procedure is known as an initiator node. Initiator node starts the process of tree construction by broadcasting `T_MSG` control packet as described in Algorithm 6.2.

Algorithm 6.2 **Tree Construction**

Data Structure for any sensor node x :
$Children(x)$: children set of node x, initialized to ϕ.
$Parent(x)$: parent of node x, initialized to ϕ.
$IsCH_x$: it is **true** if any node x is a cluster head.
$Parent\_Selected_x$: set to **true** when the sensor node x selects its parent, initialized to **false**.
$T\_MSGSent_x$: set to **true** when the sensor node x sends `T_MSG` packet, initialized to **false**.

```
node x receives following packets from node y:

T_MSG : < T_MSG, id_y, Parent(y) >
if (IsCH_x == true) then
    if (id_x == Parent(y)) then
        Children(x) ← Children(x) ∪ {id_y};
    else if (Parent_Selected_x == false) then
        Parent(x) ← id_y;
        Parent_Selected_x ← true;
        if ((T_MSGSent_x == false)) then
            T_MSGSent_x ← true;
            l_rb(T_MSG, id_x, Parent(x));          ▷ Broadcast T_MSG packet
        else
            Drop the packet;
        end if
    end if
else
    Drop the packet;
end if
```

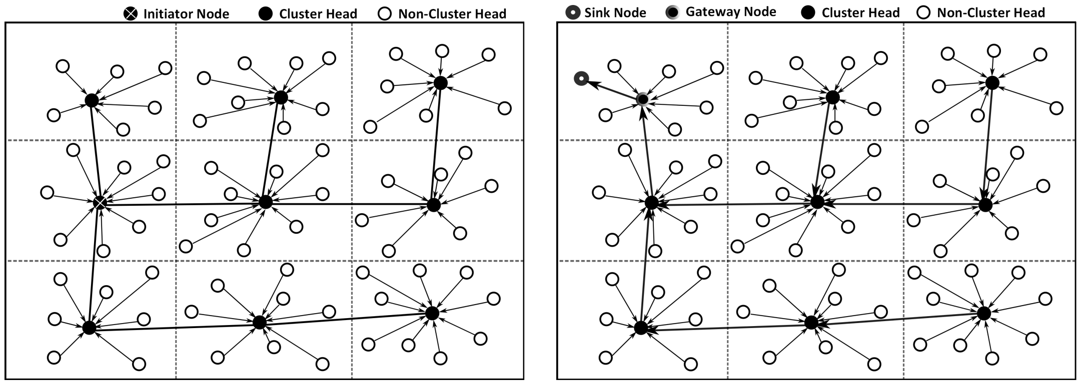
When the cluster heads of the different grids receive the `T_MSG` they perform following operations:

- If the recipient is the cluster head, it checks the sender's parent id and if it is the same as the receiver node id, then include the sender id in the children list $Children(x)$.
- If it has not selected any parent, then select sender node as its parent.
- If $T\_MSGSent$ is false, then broadcast `T_MSG` packet with modified parameter to the network.

In this way, the tree is constructed with the parent and child nodes as shown in Figure 6.3(a). The purpose of the tree formation is to make sure that the network is connected. The link between the parent and child node would be bidirectional.

6.3.4 Mobile Sink Management

The sink follows the random waypoint mobility model. It is required to manage the sink mobility. The sink moves from one location to another and collects the data. In the new position, sink waits to gather the data, this duration is called



(a) Initial view of Tree Construction. (b) Mobile sink management through the gateway node.

Figure 6.3: Tree Construction and Mobile Sink Management.

pause time (δ). One of the closest cluster head elected as a gateway node by the sink. The gateway node informs the rest of the cluster head through the tree. The cluster head nodes make the link towards the gateway node for transmitting the data as demonstrated in Figure 6.3(b). The detailed packet communication for sink management is illustrated in Algorithm 6.3. When the mobile sink reaches to the new position, it broadcasts a `Beacon` packet. The `Beacon` packet consists of sink *id*. The cluster head that receives the beacon should reply the sink with `BeaconRelay` packet. The `BeaconReply` packet consists of its *id* and the sink *id*. When the sink receives the first `BeaconReply` packet, it selects that sender cluster head as the gateway and transmits a `Gateway` packet. The gateway packet consists of sink *id* and selected gateway node *id*. When the selected gateway node receives the packet, it selects the next node as the sink to transmit the data and broadcasts the acknowledgment (`ACK`) packet. The `ACK` packet consists of the sender *id* and gateway node *id*. The recipient cluster head performs the following operations:

- Checks if the `ACK` packet sender is a parent or a child, then
- Checks if the `ACK` packet is not for the previous gateway node, then
- Selects the gateway node as newly selected gateway node and selects *next_node* as sender node *id*.
- Forwards the `ACK` with its *id* and gateway node *id*.

In this way, each cluster head selects the next cluster head to transmit the data. When the sink moves from its current position, it sends a `STOP` signal to the gateway node. The gateway node forwards the `STOP` signal in the network. So that all the cluster heads halt the transmission until the sink selects the new gateway. It increases the data delivery ratio and decreases the data loss.

Algorithm 6.3 **Mobile Sink Management**
Data Structure for any sensor node x and sink:
$Gateway_{sink}$: gateway node selected by the sink.
$Gateway\_selected$: set to **true** once the sink chooses the gateway node, initialized to **false**.
$next\_node_x$: the cluster head x selects the next cluster head for data transmission.
$SendData_x$: set to **true** once the cluster head chooses the $next\_node_x$ for data transmission, initialized to **false**.
$IsCH_x$: it is **true** if any node x is a cluster head.
$Gateway_x$: gateway node selected by the node x.

---

node x receives following packets from the *sink*:

`Beacon`: $< \texttt{Beacon}, id_{sink} >$
if $(IsCH)$ **then**
  $l\_rf(\texttt{BeaconReply}, id_x, id_{sink})$; ▷ Unicast the `BeaconReply` packet to the sink.
end if

the *sink* receives following packets from cluster head y:

`BeaconReply`: $< \texttt{BeaconReply}, id_y, id_{sink} >$
if $(Gateway\_selected == false)$ **then**
  $Gateway_{sink} \leftarrow id_y$;
  $Gateway\_selected \leftarrow true$;
  $l\_rf(\texttt{Gateway}, id_{sink}, Gateway_{sink})$; ▷ the sink unicasts the `Gateway` packet to the selected gateway node.
else
  Drop the packet;
end if

cluster head node x receives following packets from the *sink*:

`Gateway`: $< \texttt{Gateway}, id_{sink}, Gateway_{sink} >$
if $(id_x == Gateway_{sink})$ **then**
  $next\_node_x \leftarrow id_{sink}$;
  $l\_rb(\texttt{ACK}, id_x, Gateway_{sink})$; ▷ Boradcast the `ACK` packet.
else
  Drop the packet;
end if

cluster head node x receives following packets from node y:

`ACK`: $< \texttt{ACK}, id_y, Gateway_{sink} >$
if $(IsCH \,\&\&\, ((id_y \in Parent(x)) \,||\, (id_y \in Children(x))))$ **then**
  if $(Gateway_x \neq Gateway_{sink})$ **then**
    $Gateway_x \leftarrow Gateway_{sink}$;
    $SendData_x \leftarrow true$;
    $next\_node_x \leftarrow id_y$;
    $l\_rb(\texttt{ACK}, id_x, Gateway_{sink})$; ▷ Boradcast the `ACK` packet.
  end if
else
  Drop the packet;
end if

6.3.5 Data Transmission

The cluster member sends their data to the cluster head and switch to sleep mode until the next time-slot. The cluster head aggregates the data. If the

SendData flag is true, then it can immediately start the data transmission to the next cluster head (*next_node*). Once the data packet reaches the gateway node, it forwards the data to the sink. The detail description is illustrated in Algorithm 6.4.

Algorithm 6.4 **Data Transmission**

Data Structure for any sensor node x :

$SendData_x$: set to **true** once the relay node chooses the $next\_node_x$ for data transmission, initialized to **false**.

$Send\_Data(x)$: node x add the pair of id and sec_no after receiving the `DATA` packet, initialized to ϕ.

```
node x will receive following packet from node y ∈ Nbr(x):

DATA : < DATA, id_source, sec_no_source, Nextnode_y >
if (id_x == Nextnode_y) then
    if (< id_source, sec_no_source > ∉ Send_Date(x)) then
        Send_Data(x) ← Send_Data(x) ∪ {id_source, sec_no_source};
        if (SendData_x == true) then
            l_rf(DATA, id_source, sec_no_source, next_node_x);    ▷ Forward the DATA packet to the next node.
        end if
    end if
else
    Drop the packet;
end if
```

The recipient node performs the following operations:

- Checks if the receiver node is the same as the next node *id*, then
- Checks if it receives the new data, then
- Adds the source *id* and sequence number in the *Send_Data* table and
- If the *SendData* flag is true, then forwards the data to its next cluster head.

6.3.6 Load Balancing

In the proposed protocol, every node can compute their residual energy. When the cluster head's energy level reaches below to the threshold value, the protocol initiates the cluster head selection process. Once the new cluster head is selected, it builds the cluster and begins the tree construction process. In this way, the protocol balances the load among the sensor nodes, and it helps to increase the lifetime of the network.

6.4 Simulation Results

To validate and compare the proposed protocol with the TEDD and DTRP in terms of performance metrics mentioned in the Chapter 2. An extensive set of experiments have been done using the Castalia (v3.2) simulator and based on the parameters shown in Table 6.1.

Parameter Name	**Value**
Network area	500×500 $meter^2$
Number of sensor nodes	200
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
δ	5 *sec*
Sink speed	(5, 10, 15, 20, 25, 30) m/sec
Mobility Model	Random Waypoint
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{proc}	5 nJ/bit
E_{low}	0.2 $nJ/second$
Simulation time	400 *sec*
MAC protocol	TMAC

Table 6.1: Simulation Parameters.

6.4.1 Average Control Packet Overhead

Figure 6.4 illustrated the average energy consumption of control packet with varying sink speed. The sensor node transmits the control packets to construct the cluster and tree and manage the sink mobility. In TEDD, DTRP and proposed protocol, the tree structure is independent of the sink mobility. However, when the role of a node changes from the relay to non-relay or non-relay to relay, in TEDD the entire tree has to construct once again. In case of DTRP, only two hop neighbors are affected. In the proposed protocol, the control packet overhead for sink management and tree reconstruction are less than the existing protocols due to fewer cluster heads.

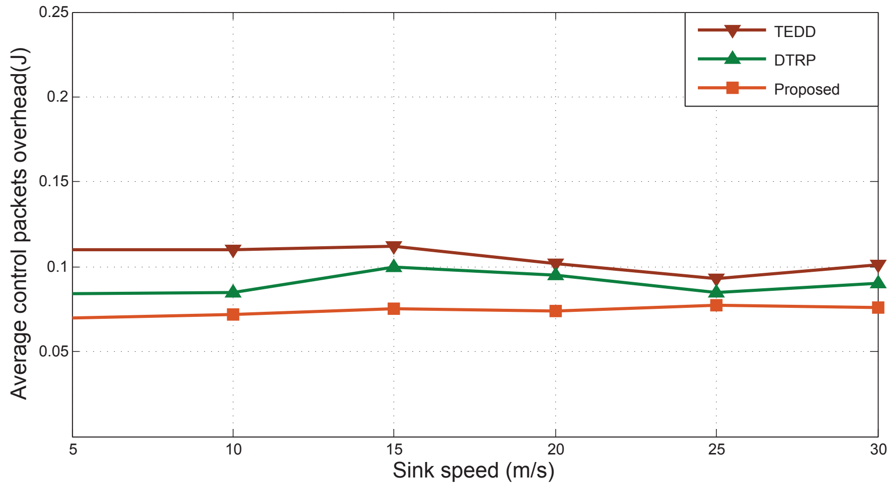


Figure 6.4: Control Packet Overhead

6.4.2 Average Energy Consumption

The average energy consumption of the nodes in the network for data and control packet is shown in the Figure 6.5. TEDD and DTRP do not aggregate the data. However, in the proposed protocol, the cluster head aggregates and transmits the data to the sink through the tree. It reduces the total data packet received by the sink. Therefore, the average energy consumption is less in the proposed protocol.

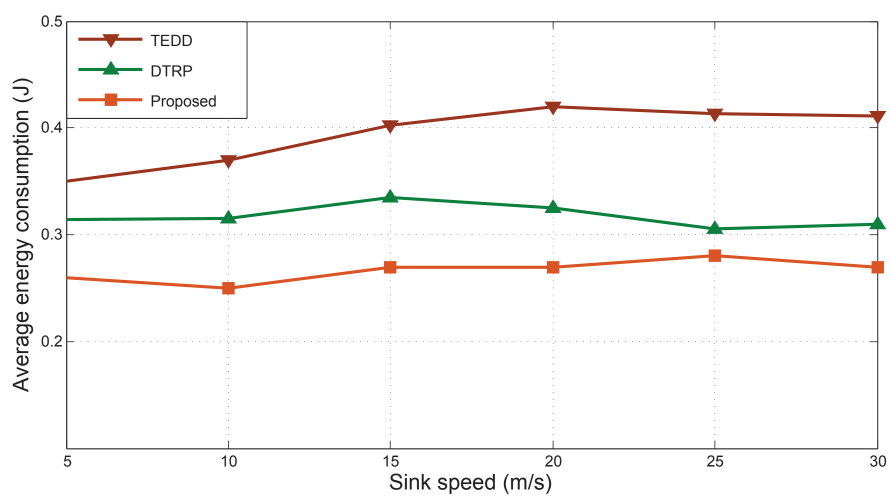


Figure 6.5: Average Energy Consumption

6.4.3 Average End-to-End Latency

It is the time duration between data generation and successful reception at the sink. Figure 6.6 shows the average end-to-end latency with various sink speeds. The proposed protocol takes less cost and time to manage the mobility of the sink and tree reconstruction than TEDD and DTRP. It is because of the tree formation using cluster head rather relay nodes.

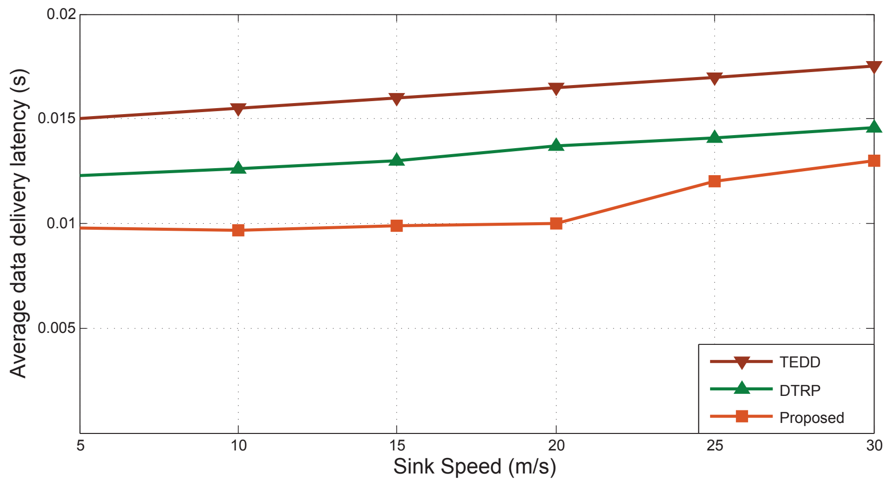


Figure 6.6: Average End-to-End Latency

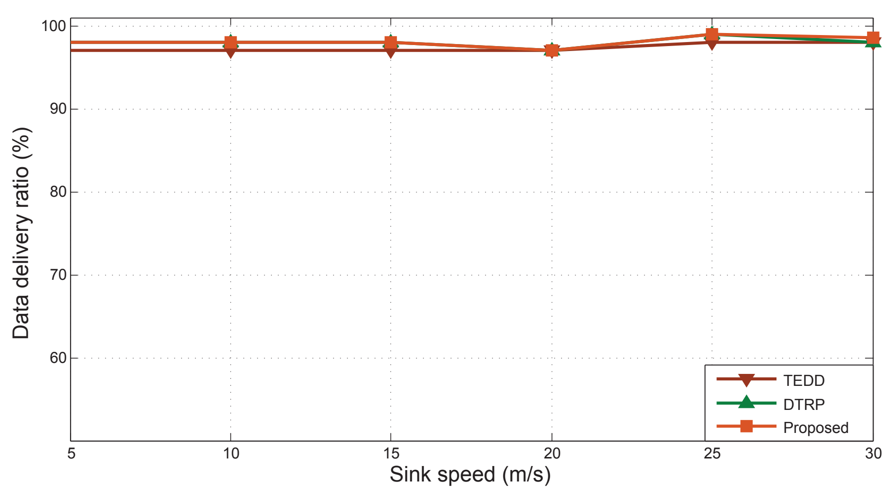


Figure 6.7: Packet Delivery Ratio

6.4.4 Packet Delivery Ratio

Figure 6.7 presents the data delivery ratio with respect to different sink speeds. Data delivery ratio shows the reliability of the network. It can be measured by the ratio between the data received by the sink and sent by the sensor nodes. The sink mobility increases the link failure, which causes data loss. The proposed protocol efficiently manages the route than TEDD and DTRP. Furthermore, in the proposed protocol, the total data transmissions are less than TEDD and DTRP. It increases the delivery ratio of the proposed protocol.

6.4.5 Network Lifetime

The network lifetime of the proposed scheme is greater than the TEDD and DTRP as shown in Figure 6.8. It is due to the less control packet overhead and aggregated data. The proposed protocol also balances the load among the sensor nodes, which makes the proposed protocol more energy-efficient and leads to the increased network lifetime.

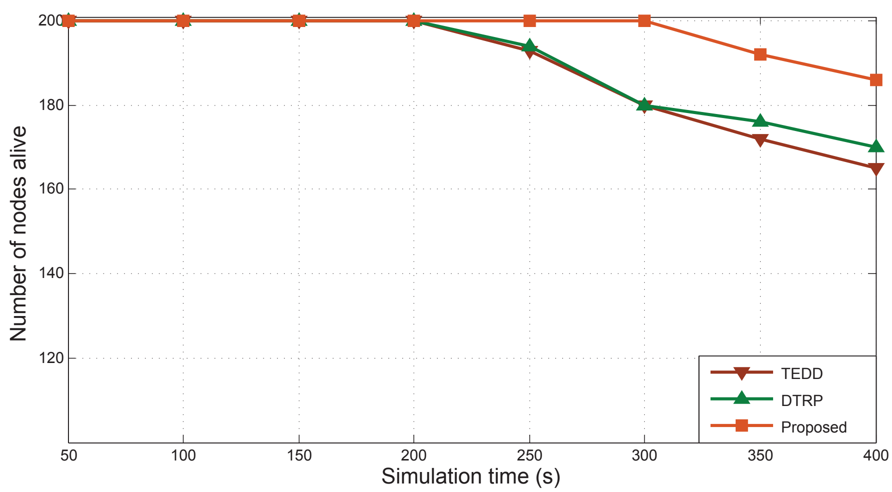


Figure 6.8: Network Lifetime

6.5 Summary

In this chapter, a clustered tree based routing protocol (CTRP) has been proposed to address the flaws of TEDD and DTRP. CTRP efficiently send the data to sink and minimize the battery power consumption of sensor nodes. A cluster is formed in each grid, and a cluster head is selected. CTRP creates a tree using these cluster heads. CTRP can manage the sink mobility without affecting the tree structure. It balances the load among the sensor nodes which increases the network lifetime. Simulation results showed that CTRP outperformed TEDD and DTRP in terms of energy consumption, end-to-end latency, data delivery ratio and network lifetime.

Chapter 7

Rendezvous based Routing Protocol with Mobile Sink

Introduction

System Model

The Proposed Protocol

Simulation Results

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Chapter 7

Rendezvous based Routing Protocol with Mobile Sink

7.1 Introduction

The network with mobile sink implicitly balances the load among the sensor nodes and reduces the chance of hotspots [103]. It can help to achieve the uniform energy consumption and prolong the lifetime. On the other hand, some problems are associated with the mobile sink. The mobile sink frequently required to send its current position information across the network. This process causes a significant energy consumption overhead. Addition to that, the mobile sink makes the sensor network dynamic in nature. Hence, it is not feasible to find the routing path prior to its requirement. Generally, in the reactive routing, the end-to-end latency is high, which can compromise the requirement of fresh data. In the event-based application, the validity of the sensor data depends on its freshness. The delayed data is of no use. So the primary requirement of the event-based application is to reduce the end-to-end latency. Latency may be affected by many factors like availability of routing path, known mobile sink location, the existence of non-interference paths, etc.

It has been observed that the rendezvous based approaches are suitable for the time-sensitive applications. They are capable of reducing the latency. In the mobile sink environment, the source node has to wait until it gets the routing path to transmit the data. In rendezvous based routing some predefined area is specified, where the source node can communicate. In some approaches like

Line Based Data Dissemination (LBDD) [75] and Grid-based energy efficient routing [74], source node can transmit the data to the rendezvous region, and the rendezvous nodes can further forward the data to the sink. Whereas, in the approaches like Railroad [76] and Ring routing [77], source node can retrieve the current position of the sink from the rendezvous region and transmit the data directly to the sink through intermediate nodes using geographical based approaches [44, 45]. In the first types of approaches, the end-to-end latency is very less, but it compromises the energy-efficiency. Whereas the second types of approaches are energy-efficient, but it compromises the latency. It motivated to propose rendezvous based routing protocol, which can be energy-efficient and takes less time to deliver the sensed data.

In this chapter, a Rendezvous based Routing Protocol (RRP) is proposed, which addresses the requirement of energy-efficiency and less end-to-end latency. In RRP, a virtual cross area is created in the middle of the network. It is called rendezvous region, and the nodes belong to this region are called backbone nodes. A tree is formed within the rendezvous region, and each sensor node can communicate with the rendezvous region. In RRP, two methods are proposed for the data transmission. In the first method, the source node transmits the data to the sink through the rendezvous region. In the second method, source node retrieves the position of the sink and transmits the data to the sink using geographical based approach [44]. The system model is defined in Section 7.2, In Section 7.3 the description of the proposed protocol is presented. The simulation result and analysis are discussed in Section 7.4 and finally, the proposed protocol is summarized in Section 7.5.

7.2 System Model

7.2.1 Network Model

The network consists of n number of sensor nodes and a sink. The sensor nodes are static, and a sink is moving within the network with the speed varying from 5 to 30 $meter/second$. A pause time (δ) for the sink is considered to collect the data. A virtual horizontal and vertical region of width w is considered. It resides in the middle portion of the network having a center position (u, v). This region has four parts such as: (i) horizontal left h_l, (ii) horizontal right h_r, (iii) vertical up v_u and (iv) vertical bottom v_b as shown in Figure 7.2(a). If the sensor node is detected any event, then it should report to the sink. The energy model for the sensor node is the same as stated in Chapter 2. Besides, the assumptions are taken in Chapter 4 the additional assumptions are considered. The Random Waypoint mobility model has been considered for the sink mobility. The sensor node can find their location information, and the node can vary their transmission range up to the maximum range R. Each node can calculate their residual energy.

7.3 The Proposed Protocol

The proposed protocol is a rendezvous based routing protocol. In this, a virtual cross area is created of width w, in the middle region of the network. These cross area acts as a rendezvous region for sensor node communication. The nodes in rendezvous area are called backbone node. A tree has been created in the cross area. This tree involves only a few backbone nodes, and it is created such a way that the boundaries can be covered. The tree nodes are responsible to forward the information from the source to the sink or from the sink to the source. The proposed protocol consists of various phases such as neighbor discovery, cross area formation, tree construction, sensor node region discovery and data transmission.

7.3.1 Neighbor Discovery

In this phase, each sensor node finds the neighbors information as discussed in the Algorithm 7.1. The initiator node broadcasts a control packet `NBR_DET`, which contains the node id, residual energy and the location information. The neighbor node that receives the `NBR_DET` packet will maintain a table called $NbrTable$. The $NbrTable$ consists of node id of the sender, its residual energy, and location. If the sender node id is already in the $NbrTable$, then the packet is dropped by the receiver node. The receiver node creates and broadcasts the `NBR_DET` control packet if it did not broadcast before. At the end of the neighbor discovery phase, each node has the one-hop neighbor list and corresponding information.

Algorithm 7.1 **Neighbor Discovery**

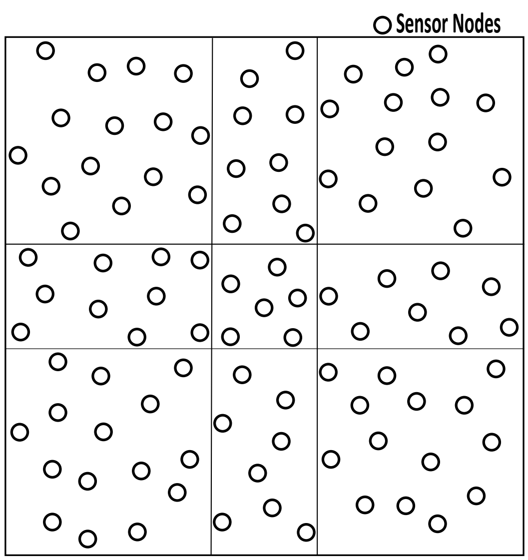
Data Structure for any sensor node x :

$Nbr(x)$: neighbor set of node x, initialized to ϕ.
$NbrTable(x)$: neighbor table of node x, initialized to ϕ.
Er_x: residual energy of any node x.
$NbrDETSent_x$: set to **true** when the sensor node x sends `NBR_DET` packet, initialized to **false**.

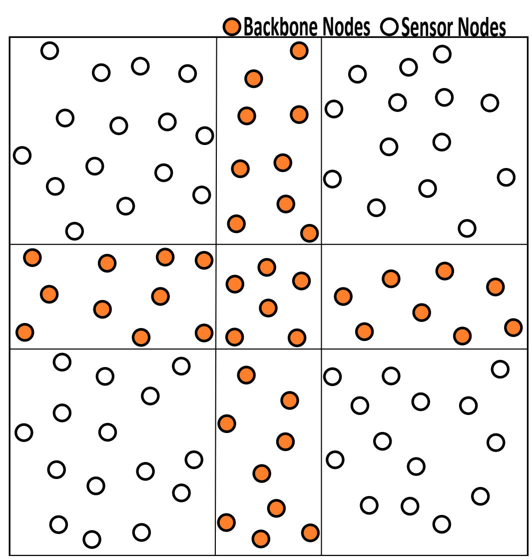
```
node x receives following packet from node y:

NBR_DET :< NBR_DET, id_y, Er_y, Loc_y >
if (y ∉ Nbr(x)) then
    Nbr(x) ← Nbr(x) ∪ {y};
    Update NbrTable(x) with < id_y, Er_y, Loc_y >;
    if (NbrDETSent_x == false) then
        NbrDETSent_x ← true;
        l_rb(NBR_DET, id_x, Er_x, Loc_x);          ▷ Broadcast NBR_DET packet
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

7.3.2 Cross Area Formation

The proposed protocol divides the sensor field into equal parts of a vertical, and a horizontal stripe called cross area as shown in Figure 7.1(a).



(a) Initial view of Rendezvous region.



(b) Initial view of Backbone nodes.

Figure 7.1: Rendezvous region and Backbone nodes.

The node belongs to the cross area are called the backbone nodes. Let's consider w is the width of the strip and maximum network area is (x_{max}, y_{max}).

So, w_x and w_y, the horizontal and vertical ranges of the backbone are defined as shown in Equation (7.1).

$$w_x = \left(\frac{x_{\max} - w}{2}\right) \; to \; \left(\frac{x_{\max} + w}{2}\right); w_y = \left(\frac{y_{\max} - w}{2}\right) \; to \; \left(\frac{y_{\max} + w}{2}\right); \quad (7.1)$$

If any sensor node belongs to the range of w_x and w_y, it can be labeled as a backbone node. In the protocol, the Cross area used as a rendezvous region. This region works as a communication point for the sensor nodes. The rendezvous region and backbone node in the network are shown in Figure 7.1.

7.3.3 Tree Construction

The tree construction is performed inside the rendezvous region. The protocol allows only some of the backbone nodes to take part in the tree construction. The boundary nodes of the four sections of rendezvous region h_r, h_l, v_u, v_b as shown in Figure 7.2(a), start the process of tree construction. Each node has the neighbor information that includes *id*, residual energy and the location. The boundary node selects one of its neighbor using the following criteria:

1. The node should be a backbone node,

   Let BB_x is true if any node x labeled as backbone node,
   $Nbr(x)$ is a set of neighbor node of x and
   z is a sensor node;
   if ($z \in Nbr(x)$ && BB_z == true) **then**
   z can be chosen by x in tree construction ▷ First criteria for node selection.
   end if

2. the residual energy of the backbone node should be greater than the threshold value,

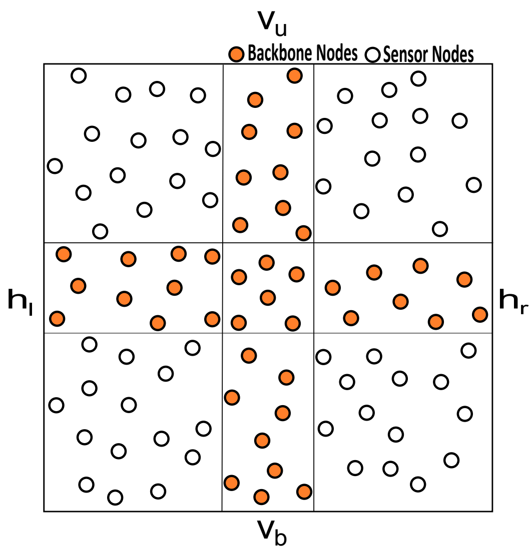
   $Er(z)$ is the residual energy of any node $z \in Nbr(x)$, then
   $Er(z) \geq E_{threshold}$ ▷ Second criteria for node selection.

3. and the sensor node should be closer to the centroid of the network.

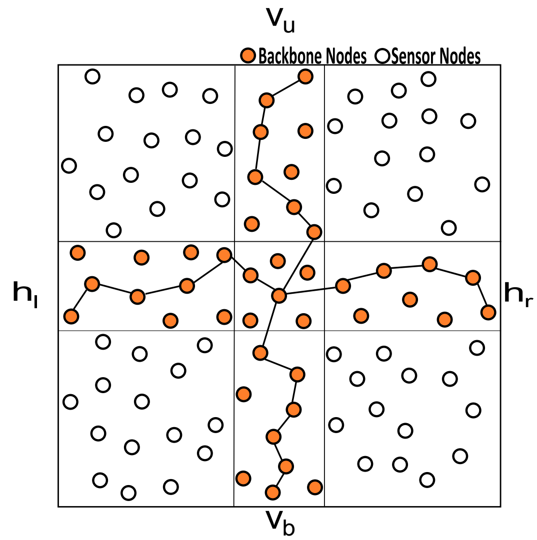
   Let z_1, z_2, z_3, ...z_j are the nodes belong to the backbone and Nbr(x) and $\mid D(z_i) \mid$ is the distance of any node z_i form the centroid of the network

   So, $z = \min_{1 \leq i \leq j}(\mid D(z_i) \mid)$ ▷ Third criteria for node selection.

After selecting one of the neighbor nodes, the boundary node transmits the control packet to the selected node for tree construction. The receiver node makes the sender node as the parent and selects the next neighbor node closest to the centroid. This process repeats until the packet initiated by the boundary node reaches the centroid of the network as shown in Figure 7.2(b).



(a) Rendezvous region with the boundary h_r, h_l, v_u and v_l.

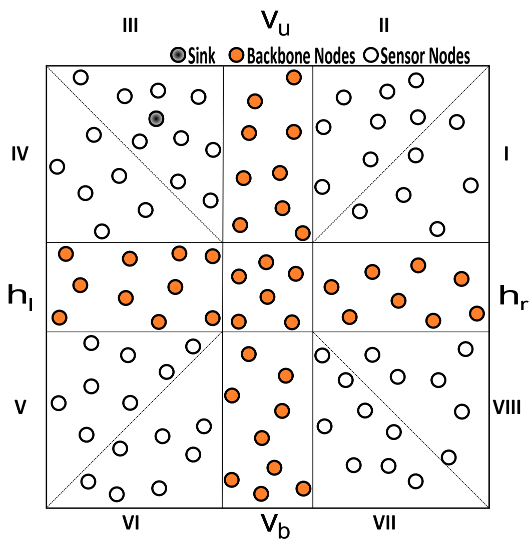


(b) Final view of tree construction.

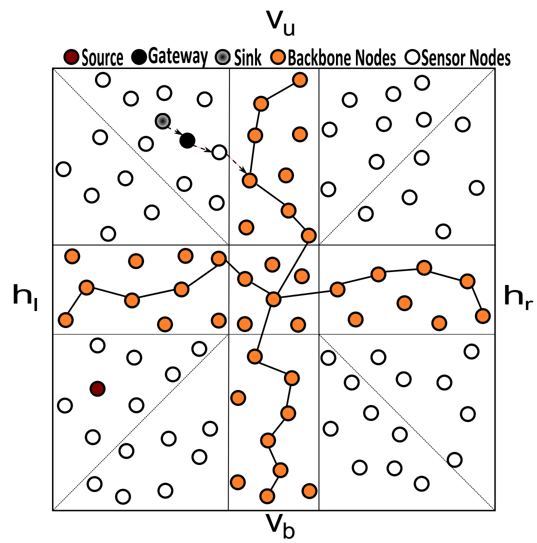
Figure 7.2: Rendezvous region and Tree within the rendezvous region.

7.3.4 Sensor Node Region Discovery

After the tree construction, the sensor node can communicate with the backbone-tree nodes. In this process, the sensor node is required to find out the region in which it belongs. So, the sensor node can find the shortest destination to communicate with the rendezvous region. The network is virtually divided into octants as illustrated in Figure 7.3(a). The sensor node follows the Algorithm 7.2 with the location information of itself and location of the centroid of the network to get the shortest destination.



(a) Virtually divided octants region.



(b) Gateway node selection.

Figure 7.3: Sensor node region discovery and Gateway node selection.

The sensor nodes can calculate the octant in which they belong using their location information (x,y). For example, if the nodes belonging to 1^{st} and 8^{th} octant, it will communicate from h_r with destination location (x, v). Similarly, 2^{nd} and 3^{rd} octant sensor node can communicate from v_u with destination location (u, y) and so on, where (u, v) are the center location of the network.

7.3.5 Data Transmission

The sensor node monitors the environment and accordingly generates the data. In the proposed protocol, the source nodes can send the data to the sink whenever they required. Two different methods are considered to send the data to the mobile sink. In the first method, the source node transmits the data to the closest backbone-tree node. The backbone-tree node forwards the data to the sink. In the second method, the source node retrieves the sink location from the nearest backbone-tree node and transmits the data directly to the sink by using the sink location. Both the methods are described in the following sections.

Algorithm 7.2 **Node Region Discovery**
variables : $\theta = 0$; $\alpha = 0$;
(u, v): center location of the network.
(x, y): any sensor node location in the network.

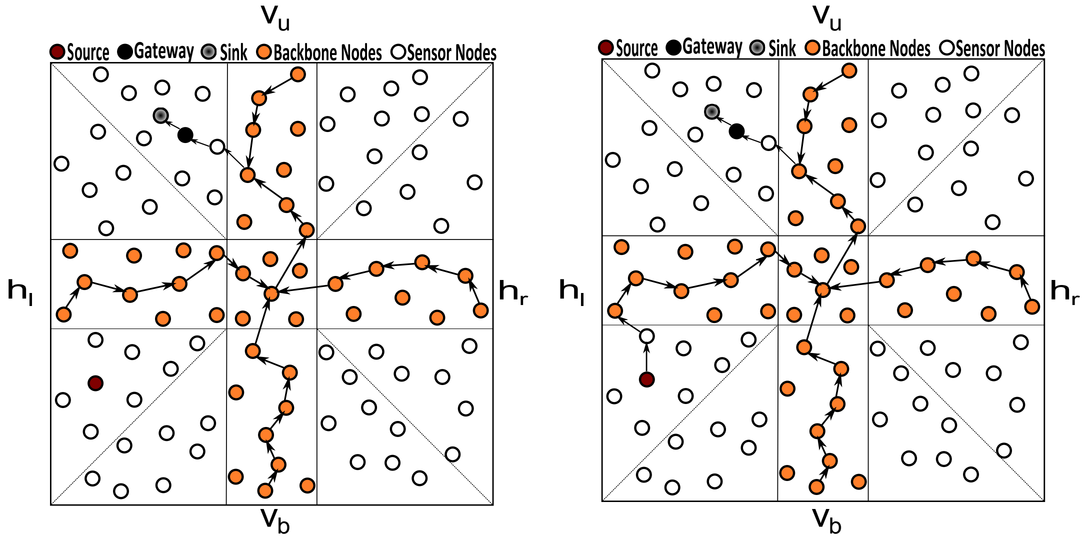
Let $\pi = 180^0$;
$C \longleftarrow (u, v)$; ▷ C is the center of the network.
for any node z in the network with location(x, y)
Let new coordinates $(A, B) \longleftarrow (x - u, y - v)$; ▷ evaluate (A, B) corresponding to the center C.
Calculate $\theta = tan^{-1}\left|\frac{B}{A}\right|$
if (A>0&&B>0) **then**
  $\alpha \longleftarrow \theta$ ▷ node with location (x, y) is in 1^{st} quadrant.
  if (α lies between $0\,to\,\pi/4$) **then**
    Node with location(x, y) belongs to 1^{st} octant and node can communicate from h_r with destination location (x, v).
  else if (α lies between $\pi/4\,to\,\pi/2$) **then**
    Node with location (x, y) belongs to 2^{nd} octant and node can communicate from v_u with destination location (u, y).
  end if
end if
if (A<0&&B>0) **then**
  $\alpha \longleftarrow \pi - \theta$ ▷ node with location (x, y) is in 2^{nd} quadrant.
  if (α lies between $\pi/2\,to\,3\pi/4$) **then**
    Node with location(x, y) belongs to 3^{rd} octant and node can communicate from v_u with destination location (u, y).
  else if (α lies between $3\pi/4\,to\,\pi$) **then**
    Node with location (x, y) belongs to 4^{th} octant and node can communicate from h_l with destination location (x, v).
  end if
end if
if (A<0&&B<0) **then**
  $\alpha \longleftarrow \pi + \theta$ ▷ node with location (x, y) is in 2^{nd} quadrant.
  if (α lies between $\pi\,to\,5\pi/4$) **then**
    Node with location(x, y) belongs to 5^{th} octant and node can communicate from h_l with destination location (x, v).
  else if (α lies between $5\pi/4\,to\,3\pi/2$) **then**
    Node with location (x, y) belongs to 6^{th} octant and node can communicate from v_b with destination location (u, y).
  end if
end if
if (A>0&&B<0) **then**
  $\alpha \longleftarrow 2\pi - \theta$ ▷ node with location (x, y) is in 2^{nd} quadrant.
  if (α lies between $3\pi/2\,to\,7\pi/4$) **then**
    Node with location(x, y) belongs to 7^{th} octant and node can communicate from v_b with destination location (u, y).
  else if (α lies between $7\pi/4\,to\,2\pi$) **then**
    Node with location (x, y) belongs to 8^{th} octant and node can communicate from h_r with destination location (x, v).
  end if
end if

7.3.6 Proposed Method 1

Mobile Sink Management

The sink is moving within the network using the random waypoint mobility model. The mobile sink always moves into the network and pause for a certain time (δ) to collect the data.

When the sink reaches to a new position, it selects a gateway node for data collection. The gateway node forwards the `ACK` packet towards the backbone node



(a) Backbone-tree node link directed towards the sink.

(b) Data transmission through the backbone-tree nodes.

Figure 7.4: Data transmission using Proposed Method 1.

through intermediate nodes. Every node that receives the `ACK` packet first time select their *next_node* as the preceding node *id* as described in the Algorithm 7.3. This process is shown in Figure 7.3(b). When the `ACK` packet reaches the backbone-tree node, it forwards the `ACK` packet to the rest of the tree. All tree nodes set their *next_node* as preceding node *id* to transmit the data as described in the Algorithm 7.3. This process is depicted in Figure 7.4(a). The detailed packet communication for sink management is discussed in Algorithm 7.3. The objective of this phase is to make the reverse link towards the sink for transmitting the data.

Data Transmission

The sensor node can send their data to the sink through the backbone-tree nodes. The sensor node finds the destination for data transmission using the Algorithm 7.2. Each sensor node has the neighbor information, which contains the neighbors' location and residual energy. It can easily send the generated data to the backbone-tree node through the neighbor nodes using the location factor (LF) as derived in the Equation (7.3). The source node can select the node that has the sufficient residual energy and minimal distance from the destination for data transmission. This process is shown in Figure 7.4(b). In a regular interval,

Algorithm 7.3 **Mobile Sink Management (Proposed Method 1)**

Data Structure for any sensor node x and sink:

$Gateway_{sink}$: gateway node selected by the sink.
$Gateway\_selected$: set to **true** once the sink chooses the gateway node, initialized to **false**.
$next\_node_x$: the cluster head x selects the next cluster head for data transmission$x$.
$SendData_x$: set to **true** once the cluster head chooses the $next\_node_x$ for data transmission, initialized to **false**.
BB_x : is true if any node x labeled as the backbone node;
$Gateway_x$: gateway node selected by the node x.

```
Node x receives following packets from the sink:

Beacon: < Beacon, id_sink >
l_rf(BeaconReply, id_x, id_sink);            ▷ Unicast the BeaconReply packet to the sink.

the sink receives following packets from y:

BeaconReply: < BeaconReply, id_y, id_sink >
if (Gateway_selected == false) then
    Gateway_sink ← id_y;
    Gateway_selected ← true;
    l_rf(Gateway, id_sink, Gateway_sink);  ▷ the sink unicasts the Gateway packet to the selected gateway node.
else
    Drop the packet;
end if

node x receives following packets from the sink:

Gateway: < Gateway, id_sink, Gateway_sink >
if (id_x == Gateway_sink) then
    next_node_x ← id_sink;
    As described in the Algorithm 7.2 the gateway node chooses the backbone and destination location.
    The node forwards the ACK packet to the node z closest to the destination using the Equation (7.3).
    l_rf(ACK, id_x, id_z, Gateway_sink);                    ▷ Forwards the ACK packet.
else
    Drop the packet;
end if

node x receives following packets from the node y ∈ Nbr(x):

ACK: < ACK, id_y, id_z, Gateway_sink >
if (id_x == id_z) then
    if (Gateway_x ≠ Gateway_sink) then
        Gateway_x ← Gateway_sink;
        SendData_x ← true;
        next_node_x ← id_y;
        if (BB_x == true && Parent_x == true) then
            Choose the node z as parent and child id;
        else
            Choose the node z closest to the destination using the Equation (7.3).
        end if
        l_rf(ACK, id_x, id_z, Gateway_sink);          ▷ Forwards the ACK packet in the tree.
    else
        Drop the packet;
    end if
else
    Drop the packet;
end if
```

each node broadcast their residual energy to update the neighbor information.

Let node i required to select the nodes from its neighbors. $Nbr(i)$ is the set of neighbors of node i. $LF(i)$ is the set of location factors of each member of $Nbr(i)$. Er_k is the residual energy of node $k \in Nbr(i)$. $(x_k,\ y_k)$ is the location information of node $k \in Nbr(i)$ and D_k is the Euclidean distance from the destination.

$$\text{Let, } Er_{\max} = \max_{k \in Nbr(i)} Er$$

then for k^{th} neighbor LF_k can be computed as

$$LF_k = \hat{E}r_k \times \frac{1}{D_k} = \frac{\hat{E}r_k}{D_k} \quad \forall k : k \in Nbr(i) \tag{7.2}$$

$$\begin{aligned} &where, \\ &\hat{E}r_k = \tfrac{Er_k}{Er_{\max}} \\ &D_k = \sqrt{(x_{dest} - x_k)^2 + (y_{dest} - y_k)^2} \end{aligned}$$

and,

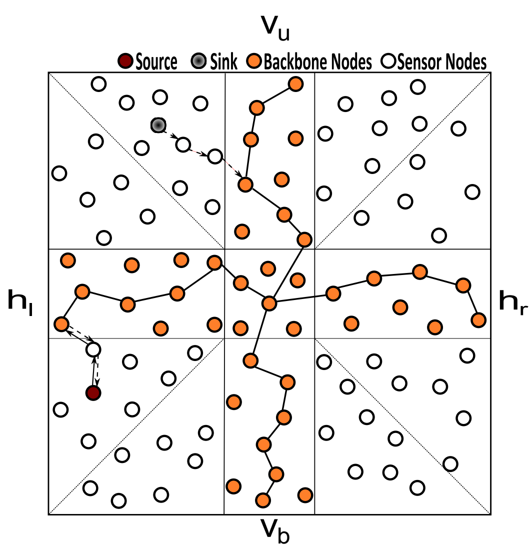
$$next\_node_i = \max\left(LF(i)\right) \tag{7.3}$$

where, $next\_node_i$ is the sensor node selected by the node i.

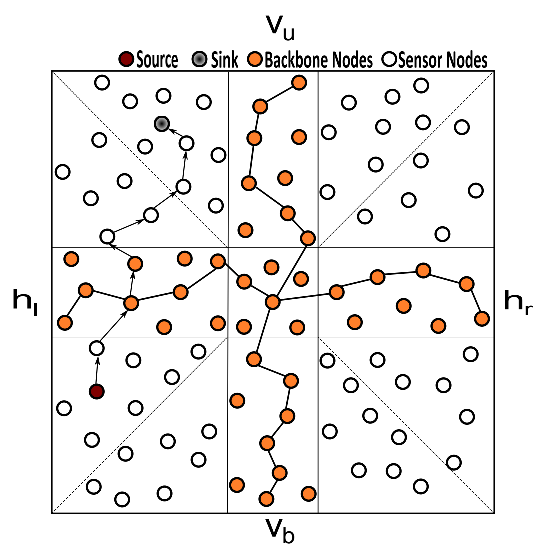
7.3.7 Proposed Method 2

Mobile Sink Management

In the second method of rendezvous based routing protocol, the sink node informs its position to the backbone-tree nodes. They have the latest location information of the sink as shown in Figure 7.5(a).



(a) Sink location recovery.



(b) Data transmission.

Figure 7.5: Data transmission using Proposed Method 2.

When a sink node moves to a new position, it broadcast a `Beacon` packet to get the neighbor information. The sink selects one of its neighbor nodes to forward the location information. Sink refers the Algorithm 7.2 and Equation (7.3) to select the forwarding node. The forwarding node again relays the sink's location to its neighbor using the same technique. When location information reaches the backbone-tree node, it disseminates the location information into the tree. The communication detail on the sink management is discussed in Algorithm 7.4.

Algorithm 7.4 Mobile Sink Management (Proposed Method 2)

Data Structure for any sensor node x and sink:

$Sink\_Loc_x$: any node x stores the sink location information.
BB_x : is **true** if any node x labeled as the backbone node, initialized as **false**.
Loc_{sink} : the location of the sink.

`Beacon`: $<$ `Beacon`, id_{sink} $>$
l_rf(`BeaconReply`, id_x, Er_x, id_{sink}); ▷ Unicast the `BeaconReply` packet to the sink.

As described in the Algorithm 7.2 the sink node chooses the backbone to send its location.
The sink node forwards the `Location` packet to the node z using the Equation (7.3).
l_rf(`Location`, $id_{sink}, Loc_{sink}, next\_node_z$); ▷ Unicast the `Location` packet to the selected node z.
Node x receives following packets from the *sink* or any node y:

`Location` : $<$ `Location`, $id_y, Loc_{sink}, next\_node_y$ $>$
if ($id_x == next\_node_y$) **then**
  if ($Sink\_Loc_x \neq Loc_{sink}$) **then**
    $Sink\_Loc_x \leftarrow Loc_{sink}$;
    if ($BB_x == true$ && $Parent(x) == true$) **then**
      Choose the node z as parent and child id;
    else
      Choose the node z closest to the destination using the Equation (7.3).
    end if
    l_rf(`Location`, $id_x, Loc_{sink}, next\_node_z$); ▷ Unicast the `Location` packet to the selected node z.
  else
    Drop the packet;
  end if
else
  Drop the packet;
end if

Sink Location Recovery and Data Transmission

To transmit the data source node needs to find the sink location. It can get the sink location from the backbone-tree nodes. For finding the sink location the source, the node makes a request to the backbone-tree node by sending a `Loc_Req` packet. When the backbone-tree node receives the request, it replies with the sink location as shown in Figure 7.5(a). The sink location recovery process is discussed in the Algorithm 7.5.

After getting the sink location, the source node transmits the data to sink through the neighbor nodes. It selects one of the neighbor nodes having sufficient residual energy and minimum distance from the sink as mentioned in Equation (7.3). When the neighbor node receives the data, it selects another node from its

Algorithm 7.5 **Sink Location Recovery (Proposed Method 2)**
Data Structure for any sensor node x:
$Sink\_Loc_x$: any node x stores the sink location information.
BB_x : is true if any node x labeled as the backbone node;
Loc_{sink} : the location of the sink.
$next\_node_x$: any sensor node x selects the next node for packet transmission .
$reverse\_link_x$: any sensor node x select the sender for sending sink location

```
As described in the Algorithm 7.2 the source node chooses the destination to send the location request.
The source node forwards the Loc_Req packet to next node using the Equation (7.3).
l_rf(Loc_Req, id_x, next_node_x);          ▷ Unicast the Location packet to the selected next node.

Node x receives following packets from any node y ∈ Nbr(x):
Loc_Req : < Loc_Req, id_y, next_node_y >
if (id_x == next_node_y) then
    reverse_link_x ← id_y;
    if (BB_x == true && Parent(x) == true) then
        l_rf(Loc_Reply, id_x, Loc_sink, reverse_link_x);     ▷ Reply the sink location to the requested node.
    else
        The node selects the next_node using the Equation (7.3).
        l_rf(Loc_Req, id_x, next_node_x);                    ▷ Unicast the Loc_Req packet to the next node.
    end if
else
    Drop the packet;
end if

Node x receives following packets from any node y ∈ Nbr(x):
Loc_Reply : < Loc_Reply, id_y, Loc_sink, reverse_link_y >
if (id_x == reverse_link_y) then
    if (id_x == id_source) then
        Sink_Loc_x ← Loc_sink;
    else
        l_rf(Loc_Reply, id_x, Loc_sink, reverse_link_x);   ▷ Unicast the Location packet to the requested node.
    end if
else
    Drop the packet;
end if
```

neighbor list using the technique as mentioned above. Figure 7.5(b) illustrated the data transmission from the source to the sink through intermediate nodes.

7.4 Simulation Results

Through the simulation, the proposed protocols performance has been analyzed and compared with the existing protocols such as Line Based Data Dissemination (LBDD) [75], Railroad [76], and Ring routing [77]. Each experiment has been performed with the varying sink speed from 5 *meter/second* to 30 *meter/second*. The impact of the sink speed in energy consumption, end-to-end latency, and data delivery ratio has been observed. An extensive set of simulation is performed based on the parameter illustrated in Table 7.1 using the Castalia (v3.2) simulator.

Parameter Name	**Value**
Network area	500×500 $meter^2$
Number of sensor nodes	200
Data packet size	512 *bytes*
Control packet size	32 *bytes*
Initial energy	$1J$
δ	5 *sec*
Sink speed	(5, 10, 15, 20, 25, 30) m/sec
Mobility Model	Random Waypoint
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{mp}	0.0013 $pJ/bit/m^4$
d_0	87 *meters*
E_{low}	0.2 $nJ/second$
Simulation time	600 *sec*
MAC protocol	TMAC

Table 7.1: Simulation Parameters.

7.4.1 Average Control Packet Overhead

The sensor node transmits the control packets to construct the rendezvous region and manage the sink mobility. The average energy consumption of control packet with varying sink speed for various protocols is illustrated in Figure 7.6. As the result shown in the graph, the control packet overhead is very less in the Proposed Method 2 as compared to the other protocols.

In LBDD, an inline-node stores the data from the source node. When that inline-node receives the query, it sends the data to the sink. The sink's query has been flooded into the rendezvous region, which causes an increased control packet overhead. In the railroad protocol, the rail construction and station formation is the one-time process. However, the process of metadata storage at station and retrieval of the sink location from the station requires the control packet exchange. In ring routing, all the ring nodes store the location of the sink. So the retrieval of the sink location is easier. However, as the network operation progresses, it requires the exchange of control packets to repair the ring. So the ring length increases, and as a result, the distance from the source or the sink causes more energy consumption. The Proposed Method 1 only needs to maintain the tree within the rendezvous region to transmit the data. The control packets are required to set the link according to the sink position. However, the Proposed Method 2 consumes less control packet overhead. It is because, the average distance between rendezvous region and the source or the sink is less than the other protocols.

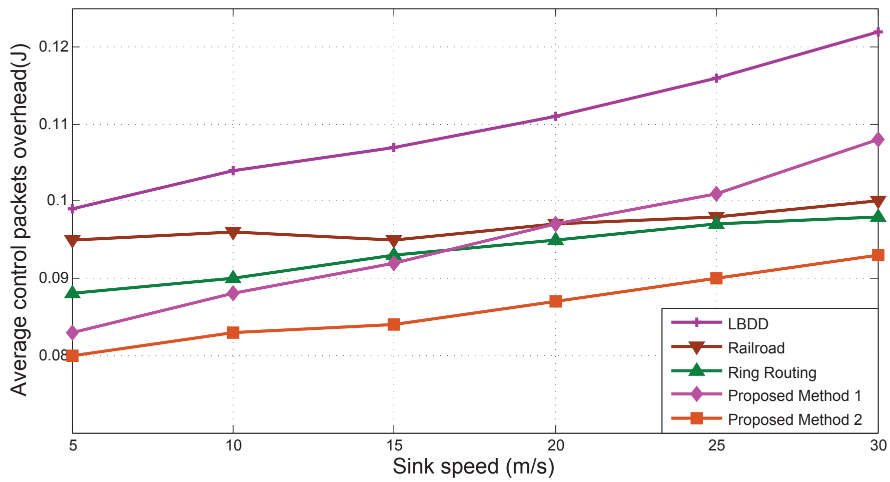


Figure 7.6: Control Packet Overhead.

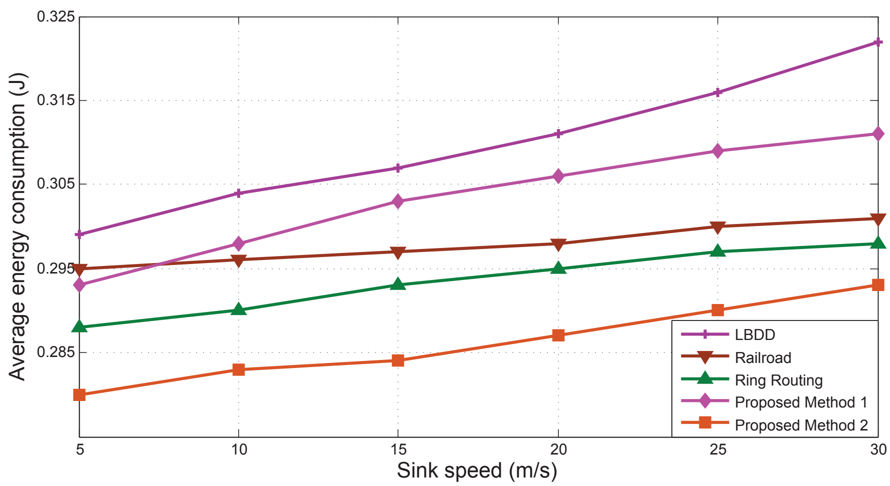


Figure 7.7: Average Energy Consumption.

7.4.2 Average Energy Consumption

The total energy consumption at each node for various protocols is shown in the Figure 7.7. It has been observed that the energy consumption of LBDD is highest due to greater control packet overhead. It stores the data from the source node and floods the sink's query in the rendezvous region. The energy consumption of the LBDD grows monotonically as the sink speed increases. The Proposed Method 1 does not require sink location, but the average path length is higher than Railroad, Ring routing and Proposed Method 2. So the overall energy consumption is more and increases according to the sink speed. In the Proposed Method 2, the average distance between source and the sink is almost the same as the Railroad and Ring routing. However, due to the less control packet overhead, the Proposed Method 2 outperforms the existing protocols.

7.4.3 Average End-to-End Latency

Figure 7.8 presents the average end-to-end latency of different protocols with various sink speeds. It depends on the time duration to find the sink's location and propagate the data to the sink. The Proposed Method 1 instantly transmits the data to the backbone tree. The tree forwards the data to the sink, as it always connected with the sink. As a result, the end-to-end delay is very less. However, in the LBDD the inline-node transmits the data as soon as it gets the sink location. The Proposed Method 2 takes less time to deliver the data as compared to Railroad and Ring routing. It is due to the shorter distance between the rendezvous region and the source node.

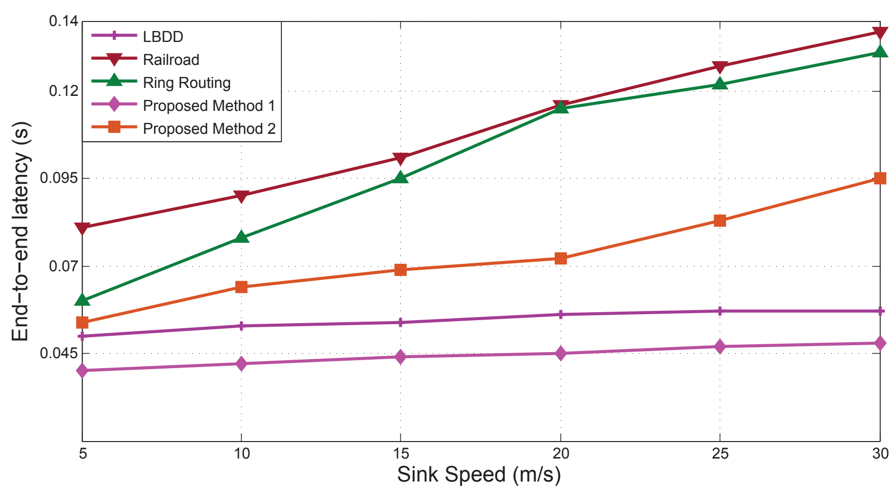


Figure 7.8: Average End-to-End Latency.

7.4.4 Packet Delivery Ratio

Figure 7.9 illustrated the data delivery ratio of various protocols. It shows the success rate of the data reception at the sink. The Proposed Method 1 maintains the connection between the tree and the sink. Hence, the delivery ratio is higher than other protocols. In LBDD, the data is stored by the inline-node and transmit to the sink as soon as it gets the location. So the possibility of data loss is less than the other protocols. In Railroad and Ring routing the time duration to get the sink's location is higher than the Proposed Method 2. It increases the delay to the data transmission. In that duration, the sink may move to the new location that causes data loss.

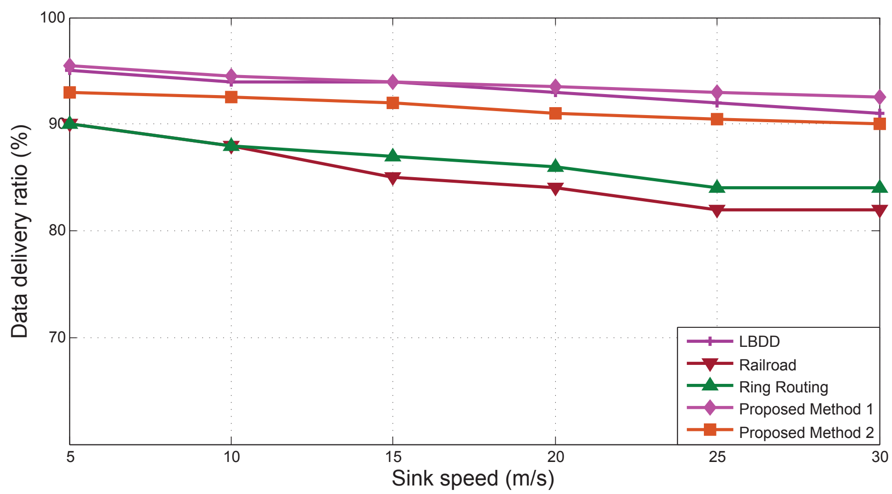


Figure 7.9: Packet Delivery Ratio

7.4.5 Network Lifetime

The energy consumption at each node and imbalance load among the sensor nodes affects the network lifetime. It is clearly shown in Figure 7.10 that, the network lifetime of the Proposed Method 2 is greater than the other protocols. The reason behind this is that it consumes fewer control packets, balances the load among the sensor nodes and follows an optimal route for data transmission.

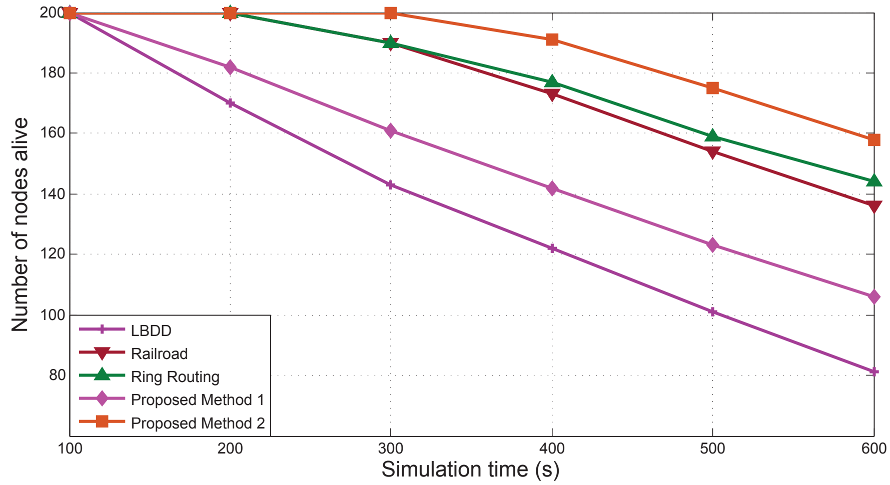


Figure 7.10: Network Lifetime

7.5 Summary

In this chapter, rendezvous based routing protocol has been proposed. It creates a rendezvous region in the middle of the network and constructs a tree within that region. In the proposed protocol, two different methods are used for data transmission. In Proposed Method 1, the tree is directed towards the sink and source node transmit the data to the sink via this tree. Whereas in Proposed Method 2, the sink transmits its location to the tree, and the source node gets the sink's location from the tree and transmits the data directly to the sink. Both the methods are compared with the existing protocols such as LBDD, Railroad, and Ring routing. From the simulation results, it has been observed that the Proposed Method 1 outperformed the existing protocols in terms of end-to-end latency and delivery ratio. The energy consumption of the Proposed Method 2 is very less than the existing protocols.

Chapter 8

Conclusions

Future Research Directions

Chapter 8

Conclusions

The work presented in the thesis has been inspired by the energy constraint of the sensor nodes. In this thesis, the protocols have been proposed for efficient routing in WSN, and evaluations were made through the simulations using Castalia (v3.2), a WSN simulator based on the OMNeT++ platform. In the thesis, six routing protocols have been proposed, out of which, two protocols are based on the static sink, and rests are based on the mobile sink.

The protocol MRP has been designed to improve the lifetime, latency and reliability through discovering multiple paths between the source and the sink. More than one routing paths are available for data transmission. If one path fails, an alternate path is used to transmit the data. Sensor nodes could conserve the energy by switching into the sleep mode if they were not involved in the routing path. It has been observed that the control packet overhead for path discovery and maintenance is very less. Thus, the improvement in the energy-efficiency has been achieved.

The cluster based multipath routing protocol with static sink (CMRP) is employed to reduce the transmission of redundant data and mitigate the traffic in the network. Further, CMRP reduces the load on the sensor nodes and provides more responsibility to the sink. Here, the sink handles cluster head selection, routing path discovery and monitoring the energy level of the sensor nodes. The sensor nodes only perform their basic functions like sensing, processing and forwarding the data. CMRP resulted in the increase in lifetime, data delivery ratio, and reduced end-to-end latency.

A tree based routing with mobile sink (TEDD) has been designed that efficiently manage the mobile sink in the network. The sink is moving within the network and gathering the data. A sensor node initiates the tree construction and becomes the root node of the tree. The link is bidirectional between relay nodes and unidirectional between a relay and non-relay node. Any sensor node can transmit their data through the relay nodes. The links are managed according to the sink position. TEDD is very robust and energy-efficient in the mobile sink environment.

The proposed dense tree based routing protocol with mobile sink (DTRP) is an extension of TEDD, which has two objectives such as minimization of control overhead, and reduction of path length. Both the objectives were achieved by reducing the number of relay nodes in the tree structure. The DTRP resulted in the increase in the lifetime and reduced end-to-end latency.

The proposed clustered tree based routing protocol with mobile sink (CTRP) has been designed to reduce the data traffic in the network and efficiently manage the mobile sink. The traffic has been reduced by the cluster head, which used aggregation technique. The number of cluster heads is restricted to the number of grids presented in the network. The tree is constructed in the network using the cluster heads as vertices. The data has been transmitted to the sink through the tree structure. The CTRP has effectively managed the load among the sensor nodes. It has been validated and compared with the TEDD and DTRP in terms of energy-efficiency, network lifetime, end-to-end latency and data delivery ratio.

The proposed rendezvous based routing protocol with mobile sink (RRP) has been designed for the time-sensitive applications, which efficiently transmit the data to the mobile sink. Each sensor node can communicate with the rendezvous region. In RRP, two data transmission methods have been proposed. In the first method, source node directly sends their sensory data to the rendezvous region. In the second method, the source node retrieves the sink's current position and transmits the data to the sink through intermediate nodes. It is found that the end-to-end latency and data delivery ratio have been improved in the first proposed method. Whereas, energy consumption and network lifetime have been improved in the second proposed method.

8.1 Future Research Directions

The research proposals made out of this thesis have opened several challenging research directions, which can be further investigated. The proposed schemes mostly deal with energy efficiency in routing protocol can be further extended to improving energy efficiency in MAC layer. The routing protocol that supports multiple static or mobile sinks will be the promising research direction to bring energy-efficiency. The requirement of security is also an emerging area of research in WSN. A light-weight security mechanism that requires low power, and less computing cost must be developed for secure routing. Additionally, the design of efficient routing protocol specific to real-time applications, which can offer to improve the Quality-of-Services (QoS) like latency, reliability, packet loss and throughput can be considered.

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2. **Suraj Sharma** and S. K. Jena, "Cluster based Multipath Routing Protocol for Wireless Sensor Networks", *Computer Communication Review*, *ACM*, Volume 45, Issue 2, Pages 14-20, 2015.

3. **Suraj Sharma** and S. K. Jena, "Data Dissemination Protocol for Mobile Sink in Wireless Sensor Networks", *Journal of Computational Engineering*, *Hindawi Publishing Corporation*, Volume 2014, Pages 1-10, 2014.

4. **Suraj Sharma** and S. K. Jena, "Energy Aware Tree based Routing Protocol for Wireless Sensor Networks", Communicated In *Digital Communications and Networks*, *Elsevier*, 2015.

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1. **Suraj Sharma**, Pratik Agarwal and S. K. Jena, "Energy Aware Multipath Routing Protocol for Wireless Sensor Networks", In *Fourth International Conference on Networks & Communications (NetCom)*, Lecture Notes in Electrical Engineering, *Springer*, Volume 131, Pages 753-760, 2013.

2. **Suraj Sharma**, Dupatta Suresh and S. K. Jena, "VGBST: A Virtual Grid-Based Backbone Structure Type Scheme for Mobile Sink based Wireless Sensor Networks", In *International Conference on Advanced Research in Computer Science Engineering & Technology (ICARCSET)*, *ACM*, Pages 1-5, 2015.

3. **Suraj Sharma** and S. K. Jena, "A Cluster-Tree based Data Dissemination Routing Protocol", In *Eleventh International Multi Conference on Information Processing (IMCIP '15)*, *Elsevier*, Pages 7-13, August 2015.

4. **Suraj Sharma** and S. K. Jena, "A Virtual Infrastructure based Routing Protocol for Wireless Sensor Networks", In 12^{th} *IEEE India International Conference (INDICON '15)*, *IEEE*, 17-20 December 2015.

Book Chapter

1. **Suraj Sharma** and S. K. Jena "Routing protocol in Wireless Sensor Networks: Research Directions", Communicated In *Handbook of Research on Advanced Wireless Sensor Network Applications, Protocols, and Architectures*, *IGI Global publisher*, USA, 2015.

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