Energy Efficient Routing Strategy for Dynamic Wireless Sensor Networks

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

by

Karyakarte Mandar Subhash

Registration No: 950903028

Under guidance of

Prof. Dr. Anil Srinivas Tavildar

Professor Emeritus, Department of Electronic and Telecommunication

Cummins College of Engineering for Women, Pune

and

Prof. Dr. Rajesh Khanna

Professor, Electronics and Communication Engineering Department

Thapar University, Patiala

COMPUTER SCIENCE AND ENGINEERING

DEPARTMENT

THAPAR UNIVERSITY, PATIALA, PUNJAB, INDIA

Certificate

I hereby certify that the work which is being presented in this thesis entitled *Energy Efficient Routing Strategy for Dynamic Wireless Sensor Networks* for the award of degree of Doctor of Philosophy submitted to Computer Science and Engineering Department of Thapar University, Patiala, Punjab, India is an authentic record of my own work carried under the supervision of Prof. Dr. Rajesh Khanna and Prof. Dr. Anil Srinivas Tavildar, The thesis refers the work of other researchers which are duly listed in the reference section. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

MSK

Karyakarte Mandar Subhash

Registration No: 950903028

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Prof. Dr. Anil Srinivas Tavildar

Professor Emeritus, Department of Electronic and Telecommunication

Cummins College of Engineering for Women, Pune

and

Prof. Dr. Rajesh Khanna

Professor, Electronics and Communication Engineering Department

Thapar University, Patiala

Abstract

Name of the student: **Karyakarte Mandar Subhash**

Registration No: **950903028.**

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Thesis supervisors: **Prof. Dr. Anil S. Tavildar** and **Prof. Dr. Rajesh Khanna**

A wireless sensor network (WSN) is the network of large number of sensor nodes that connect to each other with or without help of existing infrastructure. A WSN base station is a huge database and receives data from sensor nodes. Each sensor node performs tasks of sensing, processing, data communication and can be deployed in locations which are difficult for humans to access. WSN systems can be broadly categorized as either static networks or mobile/ dynamic networks. Static sensor network involves setting up a network where the sensor nodes are arranged in fixed positions. Dynamic or Mobile WSNs (MWSNs) contain mobile nodes and are suitable for applications involving obtaining information from moving objects such as animals or humans where sensor nodes need to be attached directly to objects and move with them. MWSNs can be used for habitat monitoring, health-care, environmental monitoring, transportation networks, underwater surveillance, military applications and many more.

A routing protocol helps to find the path from sensor node to the sink. Routing in MWSNs has several challenges as against static sensor networks due to dynamic conditions. Energy is the most constrained resource as the sensor nodes are battery operated and preferably used in remote environments.

The major contribution of the thesis is proposition of two new routing protocols namely Connectivity Based Energy Efficient Opportunistic Robust (CBEEOR) routing and Connectivity-based Cross-layer Opportunistic Forwarding (CCOF) for routing in MWSNs and an approach for predicting the network lifetime based on residual energy of node . Both the protocols use a neighbour node list prioritized on the basis of expected cost of forwarding the packet called as prioritized forwarder list. Conclusions of the research work are crisply, pointing towards the possible areas of future research in this field. In CBEEOR, expected cost of forwarding is determined as combination of packet transmission cost, expected packet relaying cost and network connectivity cost. CBEEOR implements a MAC layer two-tier delay mechanism to have forwarding agreement among the nodes in prioritized forwarder list. Whereas, CCOF computes the expected cost of forwarding as combination of packet transmission cost and expected packet relaying cost. The packet transmission cost and expected relaying cost is determined jointly using energy consumption and algebraic connectivity of the network. In CCOF protocol , a single-tier forwarding agreement is implemented for coordination among the nodes in the forwarder list. Both the protocols are simulated using ns2 and their performances are evaluated against the performance metrics like energy consumption, packet delivery, delay and overheads. An approach for network lifetime prediction based on highest value energy depletion rate is proposed. This approach is used to estimate the lifetime of WSN implemented using waspmote nodes. The results of network lifetime estimation are validated by measuring the lifetime until it becomes non-functional. Also CCOF is also implemented on waspmote hardware platform for measuring the lifetime of the

network.

The results of the above research work are published to research community in form of peer-reviewed journal publications and national conference publications.

List of Publications

SCI Indexed Publications

1. Mandar Karyakarte, Anil S. Tavildar and Rajesh Khanna "Connectivity Based Energy Efficient Opportunistic Robust Routing for Mobile Wireless Sensor Networks", Springer Wireless Personal Communications, Vol 84, issue 1, DOI 10.1007/s11277-015-2658-x SCIE indexed, Impact factor: 0.98.

2. Mandar Karyakarte, Anil S. Tavildar and Rajesh Khanna "Connectivity-based Cross-layer Opportunistic Forwarding for MWSNs", Taylor and Francis IETE Journal of Research Feb 2015 ISSN 0377-2063 (Print), 0974-780X,SCIE indexed, Impact factor: 0.19, available online 13-04-2015.

Other Publications

1. Mandar Karyakarte, Anil S tavildar, Rajaesh Khanna, "Performance Evaluation of different mobility models for mobile wireless sensor networks using AODV", published in IJCNWMC ISSN 2250-1568. ISSN 2250-1568.
2. Mandar Karyakarte, Anil S Tavildar and Rajesh Khanna, "Network Lifetime Measurements for wireless sensor networks", ICEIT conference on advances in mobile communications, Networking and computing, April 2015.
3. Mandar Karyakarte, Anil S tavildar, Rajesh Khanna, "A Prediction of Network Lifetime and Effect of Node Deployment on Lifetime of MWSNs" IICEIT conference on advances in mobile communications, Networking and computing 27-28 Sept 2013.

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Above all, I bow my head and express my gratitude to **Almighty God**, who was always there when I really needed.

Karyakarte Mandar Subhash
Registration No: 950903028

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Dedicated to

God Almighty,

My Parents,

My Teachers,

My Spouse,

And

My Daughter Little Angel "Tanaya"

For all the strength extended to me which helped to sustain during this journey.

Chapter 1

Introduction

The chapter presents introduction to wireless sensor networks (WSNs) including sensor node architecture, protocol stack and applications of wireless sensor network. The motivation for the research work, research gap along with the objectives of the research work are briefly described. The chapter concludes with contributions of the research work and organization of thesis.

1.1 Wireless Sensor Networks

A wireless sensor network (WSN) is the network of several sensor nodes working together to sense and collect information from the environment in which the network is deployed. The sensed information is then transmitted to a base station for post-processing over a single or multi-hop wireless links [4]. WSNs will have a vital role in areas which lack backbone communication infrastructure, but the network-based applications would be more suitable to perform the tasks [21]. WSNs can be viewed as network of various devices that connect to each other with or without help of existing infrastructure. A WSN base station is equipped with a database in which the sensed information about the phenomena being monitored is recorded. Each sensor node will perform tasks of sensing, processing and communication [35]. Developments in processor, memory and radio technology have helped to have miniature sensor devices that can be used cooperatively to develop a sensor network system

[47]. These miniature devices can be placed for monitoring locations which are difficult for humans to dwell. A sensor network system consisting of such devices can be applied for a large variety of applications, for example habitat monitoring, heritage architecture monitoring, environmental monitoring, crop monitoring, maritime monitoring, rare species monitoring and protection, smart city applications, glacial monitoring, mine monitoring and even epidemic control in human society [36], [94] and [95].

WSNs can be deployed as either static networks or mobile networks depending on the requirements of the application for which system is developed. Static sensor network involves setting up a network in which the sensor devices are placed at pre-determined positions [27]. A multi-hop communication is followed, if the sink or base station is not within the transmission range of sensor node. A routing protocol helps to find the path from sensor node to the sink for successful delivery of data [107]. However, the applications having inherent mobility cannot be effectively monitored using static WSN. For the applications in which the phenomena being monitored is mobile such as animals or humans, it may be a case that the sensor nodes need to be coupled with such phenomena. Such network of sensor devices is called as mobile wireless sensor network (MWSN) or dynamic WSN. The nodes in MWSN cannot form a steady routing structure like static sensor networks [84]. The mobility of nodes disturbs the routes frequently, alters topology i.e. structure of the network. Routing in MWSNs has several more challenges as against static sensor networks due to dynamic network conditions and need to mitigate these challenges for successful delivery of higher percentage of the gathered data.

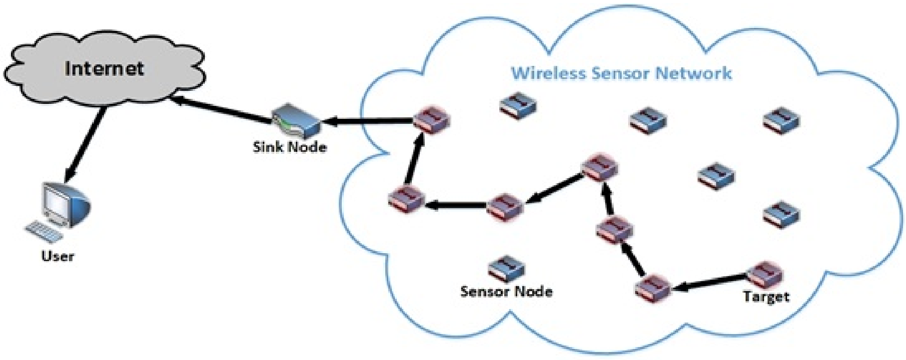


Figure 1.1: A Typical WSN [POSTECH]

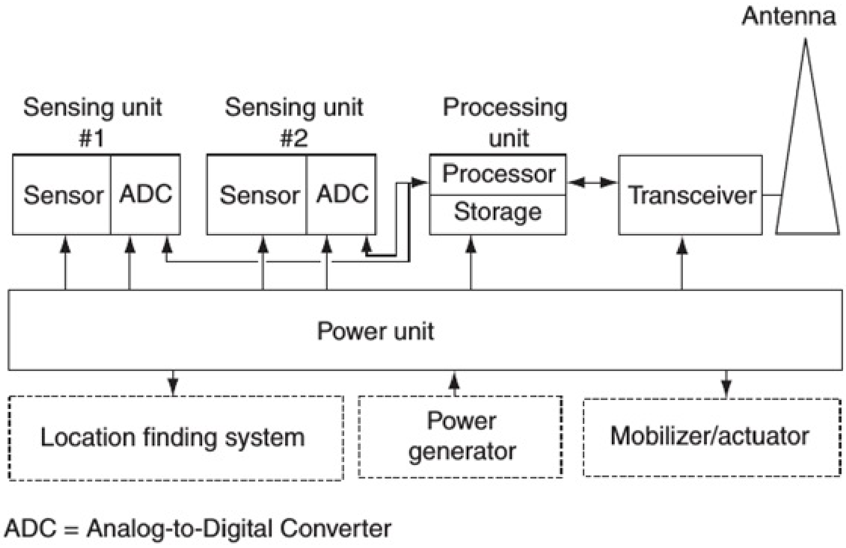


Figure 1.2: A typical sensor node architecture

The communication in sensor network is shown in Figure 1.1. Sensor nodes are placed in random locations (e.g. thrown from container or aeroplane etc.) for sensing an environment for parameters relevant to application like air quality, soil moisture, atmospheric humidity, temperature etc. As per the requirements of the WSN application each node has a ability to sense the surroundings, as well as act as repeater to forward the data to the sink. Typical sensor node architecture is shown in Figure 1.2 [104]. The WSN node consists of:

- Power unit (battery, solar panel etc.)
- Data acquisition or sensing unit (sensors, analog-digital converter etc.)
- Processing unit (micro-controller, memory etc.)
- Communication unit (transreceiver, antenna etc.)
- Other application-specific units (GPS unit).

Each sensor node consists a protocol stack for communication very similar to Open Systems Interconnection (OSI) model as shown in Figure 1.3. The physical layer is responsible for reliable channel and data link layer manages channel characteristics. Network layer performs route determination and packet forwarding [101]. Reliability

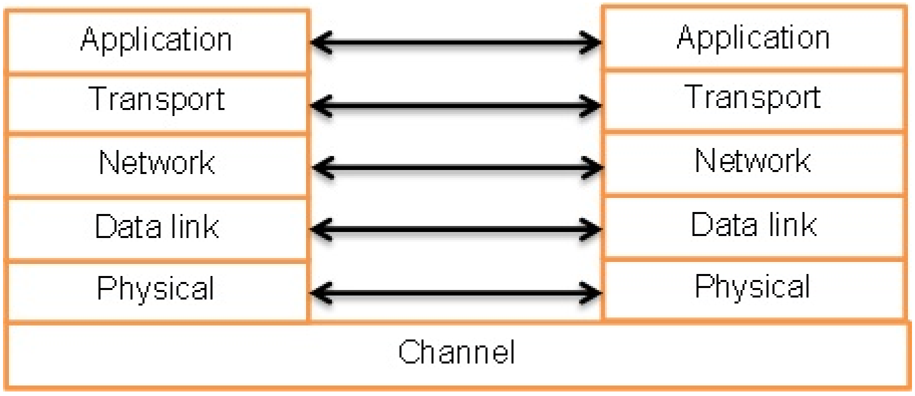


FIGURE 1.3: Protocol stack for WSN

of service between two end devices is ensured transport layer. Application layer is responsible for sensing and collecting the data

WSNs require nodes that will operate over several months before the battery is replaced. Lifetime of a WSN related with the battery energy consumption at each node in the network. Therefore power requirement of the sensing systems is the most important design constraint. The antenna, communication circuitry, finding the path for data forwarding and data packet relaying draw the most of the available power during the network operations [47].

Minimizing the energy consumption is the key for increased lifetime of sensor networks. Advances in very large scale integration (VLSI) help to reduce the power requirements of communication circuitry and energy efficient routing protocol can help for energy saving as substantial power expenses are incurred for data transmission and reception [104].

1.2 Applications of WSNs

WSNs have various diverse applications that involve monitoring and recording the events happening in and around a phenomena [104]. Some of the notable applications are illustrated in the following paragraphs,

- **Habitat and Wildlife monitoring:** Monitoring animals and birds etc. using sensor devices for studying behaviour of particular species etc. Great Duck

Island experiment for monitoring the behaviour of seabird named petrel related to climatic conditions on the island is a well-known experiment [79].

- **Military surveillance:** Sensor nodes are useful for monitoring infiltration, tank movements, troop activities, sniper's location etc. in the areas which lack fixed communication framework [7]. Exscal [8] is boundary security application implemented is one of the largest working WSN.
- **Crop monitoring:** WSNs can be useful for providing information related to soil moisture, humidity, temperature, pests etc. which will help farmers to improve the quality and quantity of the crop. Hwang et. al. [50] have implemented a agricultural monitoring system to monitor soil parameters for increasing the crop yield.
- **Industrial monitoring and process control:** WSNs are used to monitor processes in industry via WSNs to flag alerts in case any threshold is violated. Environments toxic for humans, inaccessible locations like underground mines etc. can be monitored using WSNs.
- **Healthcare:** Wearable sensors can be used to monitor patient's health or to help a disabled person to perform his activities with ease. Sensors can be used to record and monitor physiological parameters like heart and pulse rate etc.
- **Smart city monitoring:** WSNs can be used for monitoring various activities in cities like street light, water distribution, vehicular traffic and pollution, parking management, waste management etc. A WSN based system for vehicular pollution monitoring has been designed at Vishwakarma Institute of Information Technology, Pune to monitor vehicular pollutants like carbon monoxide, carbon dioxide. The project is funded by Rajiv Gandhi Science and Technology Commission, Government of Maharashtra.

1.3 Motivation and Objectives

MWSN consists of several number of mobile sensor devices in which the mobility of nodes depends upon application wherein nodes may exhibit a coordinated movement for e.g., monitoring point-of-interest or may be independent of each other for e.g. habitat monitoring. MWSNs have large number of applications which require monitoring the large areas or areas that are rarely reachable. The sensor nodes continue to monitor the area for months before the battery dies or are replaced. MWSNs are used for habitat monitoring, perimeter surveillance, industrial process control, health-care, environmental monitoring, transportation networks, underwater surveillance and many more. The following are properties of MWSNs

- Ad-hoc single-hop or multi-hop communication.
- Network scalability.
- Dynamic topology.
- Intermittent connectivity.
- Distributed processing.
- Many-to-one communication.
- In-network processing.
- Dense deployment.

Energy is the most constrained resource as the sensor nodes are battery operated and preferably used in remote environments . Path selection for data forwarding, data transmission and reception primarily draw major chunk of energy consumed for data communication. Therefore it is necessary to minimize the energy requirements for communicating the data from source to the sink. It is possible to minimize energy consumption if the routing algorithms are optimised to forward data using less amount of power [113]. Energy efficient routing protocols designed for the static sensor networks consume more energy as the design lacks ability to respond to frequent path breakages in mobile environment. Path re-computation increases overheads as well as overall energy consumption of the network [88]. So the routing constraints in MWSNs are much different compared to static WSNs due to highly constrained nature of the network making the static WSNs routing protocol unsuitable. In general, the challenges for design of routing protocol for MWSNs are summarized below:

- Energy efficiency i.e. low energy consumption,

- Sensor/link heterogeneity,
- Mobility tolerance,
- Fault tolerance,
- Node deployment,
- Scalability,
- Data reporting method.

In this thesis entitled as "Energy Efficient Routing Strategy for Dynamic Wireless Sensor Networks" the aim is to design the routing protocol which will reduce energy consumption, as well as efficiently perform data delivery in dynamic topology environment. The objectives of the proposed while commencing the research work were as follows

1. Study and simulations of existing Algorithms for understanding the present status of routing in dynamic wireless sensor networks.
2. Proposing and simulation of an energy efficient routing algorithm for dynamic wireless sensor network and its performance evaluation.
3. Quantitative evaluation of the simulated algorithm for both energy efficiency and topology-awareness.

1.4 Contributions of this Dissertation

The following are the contributions based on the work done

1. Transmission and reception of packet are major energy consuming activities, so number of packets exchanged for path building and maintenance are reduced.
2. The retransmissions required due to unavailability of the node on the intended path are eliminated with the help of broadcast nature of wireless transmissions and neighbourhood nodes.

3. The usefulness of algebraic connectivity concept for mobile wireless sensor networks is demonstrated.
4. The protocols designed are quite suitable to changing topology due to node mobility
5. We propose connectivity based energy efficient opportunistic robust (CBEEOR) and connectivity-based cross-layer opportunistic forwarding (CCOF) routing protocols that build routes in mobile environments using localized information.
6. Mathematical formulation showing how opportunistic routing is better than traditional routing in MWSNs.
7. Network lifetime estimation using simulations and implementation on hardware motes.

1.5 Organization of Thesis

- Chapter 2 presents an outline literature studied during the conduction of work. It starts with mobility issues; routing challenges for MWSNs are briefly discussed. A brief review of routing protocols for MANETs, classification and review of routing protocols for WSNs/ MWSNS to investigate their support for node mobility and provide robustness is presented. Cooperative and Opportunistic routing protocols for MWSNs are investigated followed by the open issues and research challenges related routing protocols for MWSNs.
- Chapter 3 presents the study of mobility models on the performance of MWSNs. This chapter concludes that performance of MWSNs degrades with increase in mobility speed irrespective of choice of mobility model. Also the choice of mobility model does not affect the design philosophy of routing protocol.
- Chapter 4 presents the design of connectivity based energy efficient opportunistic robust (CBEEOR) routing protocol and its performance in comparison with energy efficient opportunistic routing (EEOR) [82] and optimal opportunistic forwarding (OOF) [73] protocols.

- Chapter 5 presents the design of connectivity-based cross-layer opportunistic forwarding (CCOF) protocol and its performance in comparison with EEOR, destination sequenced distance vector (DSDV) [92] and adhoc on-demand multipath distance vector (AOMDV) [83] routing protocol.
- Chapter 6 briefly discuss as the network lifetime prediction model and its estimation using simulations of CCOF, EEOR, AOMDV and DSDV protocols as well as measurement based on implementation of CCOF, EEOR, AOMDV protocols using selected hardware motes.
- Chapter 7 presents conclusions and future research directions followed by appendices and bibliography for this research work.

Chapter 2

Literature Survey

This chapter presents a brief literature review of routing protocols for WSNs. The review starts with investigating MANET routing protocols. Taxonomy of routing protocols for WSNs, appropriateness of traditional energy efficient WSNs routing protocols for MWSNs are briefly discussed. In the later part of chapter we briefly present a review of cooperative and opportunistic routing (OR). A brief explanation stating how OR is different than traditional routing followed by a detailed review of OR is presented along with challenges and open issues for further research.

2.1 Routing Challenges in WSNs

Routing is the vital concept for discovering a communication path between source sensor device and target i.e. sink or base station. Shortest path algorithms are best when the network is perfect, static, highly connected and has global information. However, shortest path routing protocols are not suitable to WSNs due to characteristics of WSNs discussed by Akyildiz et. al. [4]. In WSNs, shortest path routing will be inefficient due to node or link failure, leading to frequent re-computation of shortest path. Also the nodes along the shortest path deplete their energy rapidly reducing the lifetime of network [24]. Routing protocol in MWSNs has to overcome additional challenges like channel fading, varying link quality, interference, node deployment, energy consumption, network dynamics, mobility and scalability.

Node deployment can be either deterministic or randomized [110]. Deterministic deployment is helpful to have pre-determined path, as long as network is stable. Randomized deployment requires routing protocol that will be adaptable to node placement and topology. Energy consumption is important as it directly affects the lifetime of network. Multi-hop short distance communication is preferred as the energy required for transmission of data is directly proportional to square of transmission distance. Routing protocol should pro-actively respond to network dynamics such as node movements, abrupt random node or link failures etc. Node mobility leads frequent changes in network topology making pre-computed routes invalid and requiring reconstruction of the routes. MWSNs can be deployed as networks with either a flat topology or hierarchical topology [5]. Initial node deployment may also lead higher energy consumption as the node placement affects the coverage of area being monitored [62]. Routing protocol should be responsive to large number of sensor nodes and high density of events. Thus routing protocol for MWSNs must accommodate changes in topology, with minimized energy consumption. In the next sub-section a brief review of MANET routing protocols is included as the protocols are designed to support mobile environments.

2.2 MANET Routing Protocols for WSNs

The designs of routing protocols for WSNs have attracted many researchers in the recent years. For MWSNs, routing protocols for mobile ad-hoc networks (MANETs) are natural choice for data forwarding as these protocols are designed to handle mobile nodes [3]. MANETs routing protocols can be classified as:

- **Pro-active routing:** These protocols are table-driven similar to wired networks and use shortest path algorithm to determine the routes. Destination sequenced distance vector (DSDV) [92] and optimal link state routing (OLSR) [30] are well-known pro-active routing protocols. The varying node position invalidates the routes computed requiring re-execution of shortest path algorithm. The re-computation of routes is short-lived i.e. the information collected after quadratic computation effort becomes invalid due to node mobility.

Therefore the pro-active routing protocols are not suitable for MWSNs as they increase overheads as well as energy consumption.

- **Reactive routing:** These protocols discover route whenever a data packet is available for forwarding the data. The strategy reduces overheads incurred for route updates for the paths which are not in use. The flip side of the on-demand routing is that the packet delay is higher as routes need to be discovered before the start of packet relay. Ad-hoc on-demand distance vector (AODV) [91] and dynamic source routing (DSR) [58], [59] are the notable examples belonging to this category of protocols. Suri and Gupta [106] have shown that DSR has better energy performance compared to AODV. As these protocols increase delay they are not suitable for time critical applications. Also on demand route discovery floods the network with probe packets for each discovery.

To summarize, MANET routing protocols are generally not suitable for MWSNs due to inherent difference among the networks which are listed below:

- WSNs have many-to-one communication using broadcast paradigm as against point-to-point to communication in MANETs.
- The number of nodes in WSNs is several order higher compared to MANETs.
- WSNs nodes are powered using a limited capacity battery and usually deployed in an unattended environments, whereas MANET devices have batteries which can be recharged.
- The low transmission power in sensor nodes leads to having communication links that are prone to higher failures compared to MANETs.

Review of routing protocols for WSNs/ MWSNs is presented in next three sections. Figure 2.1 illustrates the organisation of literature review. Section 2.3 presents review of traditional routing protocols. The review of cooperative and opportunistic routing protocols is presented in Section 2.4 and Section 2.5 respectively.

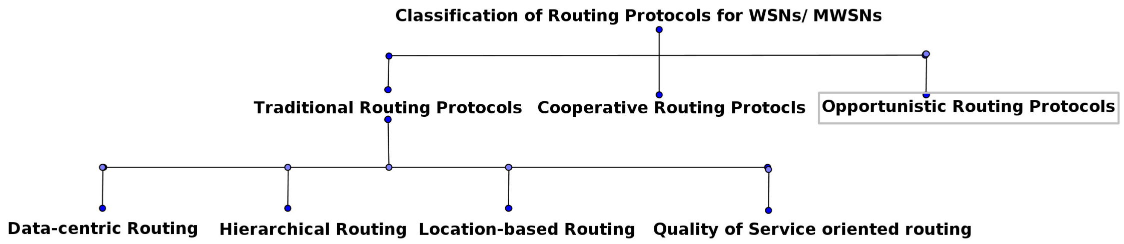


Figure 2.1: Classification of routing protocols for MWSNs

2.3 Classification and Review of Routing Protocols for WSNs/ MWSNs

In this section a brief description related to classification of traditional routing protocols for WSNs/ MWSNs is presented. The authors Al-Karaki and Kamal[5], Sohraby et. al[104] and Akyildiz et. al [4] have presented detailed surveys of traditional routing protocols for WSNs/ MWSNs. As shown in Figure 2.1 , the traditional routing protocols can be classified into four broad categories, which are briefly described below.

- **Data-centric Routing:** Sensor devices deployed in WSN area generate data and independently transmit the same to the sink which increases the data traffic. Further the data sensed in close vicinity has high degree of data redundancy. Moreover, the nodes in WSNs are randomly deployed and do not have global identities like traditional Internet Protocol (IP) networks. It is necessary for WSN routing protocols to be data centric as against address centric as well as perform data aggregation to mitigate inefficiency in energy consumption. This class of protocols are query-driven initiated by the sink. WSN area is divided into regions and sinks initiates queries region by region. The data -centric protocols are not suitable for MWSNs as they are not designed to handle dense networks and node mobility.
- **Hierarchical Routing:** Clustering or hierarchical topology is proposed to handle node density and scalability to cover a larger area. As against clustering, a flat network can cause the gateway node to become overloaded under

such constraints which will lead to increased latency in delivery of event status. The hierarchical forwarding aims at minimizing the energy consumption of nodes by establishing short range multi-hop communication within a particular cluster. Further, optimisation strategies like data aggregation and fusion [43] can be used to decrease the effective number of packets to be transmitted to the sink.

- **Location-based or Geographical Routing:** In this category, nodes position information is considered while forwarding the data in an energy-efficient way. Euclidean distance between the two nodes is calculated using the position values of each node so that energy consumption can be estimated. The position values could be absolute i.e. determined using global positioning system or may be relative to any absolute reference position like position of base station. For example, in point of interest monitoring, the query can be forwarded to specific sensor nodes thus reducing the effective number of data transmissions. These protocols suitable for routing in MANETs, as well as can also be implemented for forwarding in WSNs.

- **Quality of Service oriented routing:** Quality of service (QoS)aware protocols use delay and reliability as performance metric for delivering data. QoS parameters are used to prioritize the packets so that time-critical traffic is given preference against non time-critical traffic. These type of protocols provide different data rates based on nature of application.

Table 2.1 crisply depicts different routing protocols proposed in each of the above categories.

Data-centric Routing	Hierarchical Routing	Location-based Routing	Quality of Service oriented routing
Sensor protocols for information via negotiation (SPIN) [61]	low energy-adaptive clustering hierarchy (LEACH) [46] & its variants [43], [45]	Minimum energy communication network (MECN) [97]	Sequential assignment routing (SAR) [103]
Directed diffusion (DD) [51]	Threshold-sensitive energy-efficient sensor network protocol (TEEN) [80],	small minimum energy communication network (SMECN) [66],	Multi-Path and Multi-SPEED Routing (MMSPEED) [38],
Rumor routing (RR) [17]	adaptive periodic threshold-sensitive energy-efficient sensor network protocol (APTEEN) [81],	geographic adaptive fidelity (GAF) [111]	Energy-aware QoS routing protocol [2],
Gradient-based routing (GBR) [37]	power-efficient gathering in sensor information systems (PEGASIS) [72],	geographical and energy aware routing (GEAR) [115]	lightweight routing protocol with QoS support (LRP-QS) [1] and
Constrained anisotropic diffusion routing (CADR) [29],	Base Station Controlled Dynamic Clustering Protocol (BCDCP) [86] and		energy efficient and QoS aware multipath based routing (EQSR) [13]
COUGAR [112],	hierarchical power-aware routing (HPAR) [67]		
Active Query forwarding In sensor networks (ACQUIRE) [100],			

TABLE 2.1: Classification of routing protocols with some examples for WSNs

As the focus of this thesis is "energy efficient routing protocol for MWSNs", the following paragraphs present a brief review of traditional routing protocols for MWSNs with a focus towards two important properties namely the ability to support node mobility and provide robustness in data delivery.

Protocols such as wireless routing protocol (WRP) [85], temporarily ordered routing algorithm (TORA) [90],flooding, gossiping [44], zone routing protocol (ZRP) [42], energy-aware temporarily ordered routing algorithm (E-TORA) [114], topology dissemination based on reverse-path forwarding (TBRPF) [87] protocol are designed for flat WSNs. Gossiping protocols like rumour routing (RR) [17] were proposed to overcome overheads of flooding by forwarding a packet to a random neighbour node. WRP, TORA, RR, flooding and TBRPF use shortest path as routing metric. ZRP, gossiping and TBRPF are robust and provide a good support for node mobility. TORA and E-TORA support mobility but are not robust. Flooding and RR have higher overheads due to duplicate transmissions. LEACH [46], low-energy adaptive clustering hierarchy centralized (LEACH-C) [45], PEGASIS [72], TEEN [80], APTEEN [81], HPAR [67], two-tier data dissemination (TTDD) [78], novel hierarchical routing protocol algorithm (NHRPA) [14], Traffic-Aware Energy Efficient routing protocol (TAEE) [74], clustering-based expanding–ring routing protocol (CBERRP) [56]are some of hierarchical protocols designed for clustered networks. PEGASIS and TTDD follow greedy approach for route selection. HPAR initially uses shortest path and later energy consumption as metric for route selection. LEACH-C, TEEN, APTEEN and NHPRA use the best route whereas LEACH uses shortest path as route metric. TAEE route metric is combination of transmission power and residual energy. LEACH and TEEN lack robustness compared to PEGASIS, APTEEN, TTDD and HPAR. The hierarchical protocols are not suitable for MWSNs as frequent node movements increase overheads for cluster head selection and re-computation of paths. NHPRA has less energy consumption compared to TEEN and DD [14], whereas TEEN and CBERRP have better energy efficiency compared to LEACH-C and LEACH [80], [56]. The hierarchical protocols are scalable but have large overheads for frequent cluster head selection in node mobility scenario, which increases the battery usage. In hierarchical protocols, cluster heads relay the data to the sink. So in case of node mobility, the cluster heads may be separated by distance greater than the transmission range, which may severely affect route performance.

DD [51] , COUGAR [112] and ACQUIRE [100] are query based protocols in which the destination node initiates a query and nodes having data related to query respond to the query. ACQUIRE uses shortest path, whereas DD and COUGAR follow a path with minimum energy consumption as route metric. DD and ACQUIRE support restricted mobility whereas all the three protocols lack robustness. SPIN family forwards the data using three tier advertise-request-data mechanism. SPIN family [31] protocols are robust and are suitable for mobile nodes. Advertisement among neighbourhood nodes is used as route metric. SPIN family has higher delay between two communicating devices and consumes lot of energy as nodes are flooded with advertisements.

Location based protocols assume that every node knows self-location and sink location. They are also alternatively referred to as geographic routing protocols. This class of protocols are robust and support node mobility and so rightly suitable for MWSNs. Geographic protocols do not maintain route table, but every node maintains the list of neighbourhood nodes using simple neighbour discovery messages. GEAR [115] uses energy aware metric for next hop selection based on nodes location relative to sink. Distance routing effect algorithm for mobility (DREAM) [12] requires every node to maintain the record of location of all the nodes in the network. Mobility leads to frequent updates in the location table thereby consuming additional bandwidth. Update overheads are minimized by sending update message at short intervals to near nodes and at long intervals for farther nodes. Implicit geographic forwarding (IGF) [16] is stateless protocol suitable for highly dynamic networks. Statelessness attribute helps each node to determine the next-hop on-demand without maintaining global topology knowledge. Route metric is joint function of remaining energy and nodes distance from sink. Partial-partition avoiding geographic routing-mobile (PAGER-M) is stateless protocol with low overheads and short path lengths. Greedy approach is used to forward the packet to the sink. Energy efficient beacon-less geographic routing (EBGR) [118] selects a next-hop relay node as a function of discrete delay proportional to nodes position relative to virtual line of sight between the source and the destination. The protocol is designed to select a next relay node in a transitional region present at close distance than the transmission range for energy savings. EBGR uses Gabriel Graphs (GG) to recover route if it encounters a hole. Panigrahi et.al. [89] have proposed greedy minimum energy consumption forwarding protocol (GMFP) in which the relay node is determined jointly using its progress and energy consumption for packet transmission and reception. Weighted energy-aware routing (WEAR) [102] calculates value for each node termed as weight using four factors namely its residual energy, position, geometric distance with respect to receiver and influence of neighbourhood nodes on itself.

A data is forwarded to a node which has minimum weight among all the neighbours. The spatial-temporal relation-based energy-efficient reliable (STEER) [23] protocol broadcasts the packet to the nodes and one of the nodes is selected as next-hop based on temporal gradient calculated by function using both spatial and temporal information. The nodes spend energy in receiving the packet in-spite of not having any packet for relaying. Aligned Virtual Coordinates for Greedy Geometric Routing (AVCS) [75] is greedy routing strategy based on virtual coordinate system. Al-Otaibi, M. and Soliman, H. [6] have proposed a location based route-less routing protocol for minimizing energy consumption. The class of location-based protocol like IGF, EBGR can mitigate the effect node mobility while forwarding the data but require re-transmissions in case of packet loss due to node or link failure. This leads higher overheads as well as considerable amount of energy requirements. Majority of location based protocols proposed even though they support node mobility, lack ability to provide robustness in routing. Cooperative caching of data packets is useful for providing robustness and can be used in MWSNs for relaying the packets. The next section presents a brief review of cooperative routing protocols to understand their ability to support node mobility and provide robustness

2.4 Review of Cooperative Routing Protocols

Cooperative routing performs data forwarding by seeking benefit of broadcast nature of wireless transmissions. For example as shown in Figure 2.2, let node u want to send data to node v and the path selected is through node b i.e. $u{-}b{-}v$. When node u transmits the data to node b, node a also hears the transmission due to broadcast nature termed as wireless broadcast advantage (WBA) [109]. WBA states that all the nodes in transmission range of a node hear the transmission; hence these nodes can serve as cache storage and take-up forwarding in case the pre-decided node is not available. If the node b fails or is unavailable or the link $u \rightarrow b$ fails then node

a which has the node u's transmitted data acts as relay node and forwards the data to node v. This strategy for routing is defined as cooperative routing. The routing protocols of this category handle path breakages occurring due to node failure, link failure or node mobility by exploiting the broadcast nature of wireless transmissions.

Cooperative routing can help to mitigate multipath fading. Xiaoxia Huang et al. [49] present robust routing protocol (RRP), which is a distributed routing protocol for MWSNs. In RRP, mobile nodes seek cooperation from neighbour nodes by en-cashing the benefit of WBA to have robustness against path breakages. Liu et. al. [76] have presented a space-time block codes (STBCs) based cooperative routing scheme with improved link energy-efficiency. A minimum energy shortest path cooperative routing protocol for clustered networks is proposed by Ge et. al. [41]. Dijkstra's algorithm [33] is used to implement the shortest path. The protocol is tested for maximising network throughput in energy-delay constrained conditions in static network. Zhou et. al. [121] has presented a channel based cooperative routing for static clustered networks. The protocol avoids data forwarding from one cluster-head to another cluster-head for increasing the energy saving as the energy requirement for long distance transmission are very much on higher side.

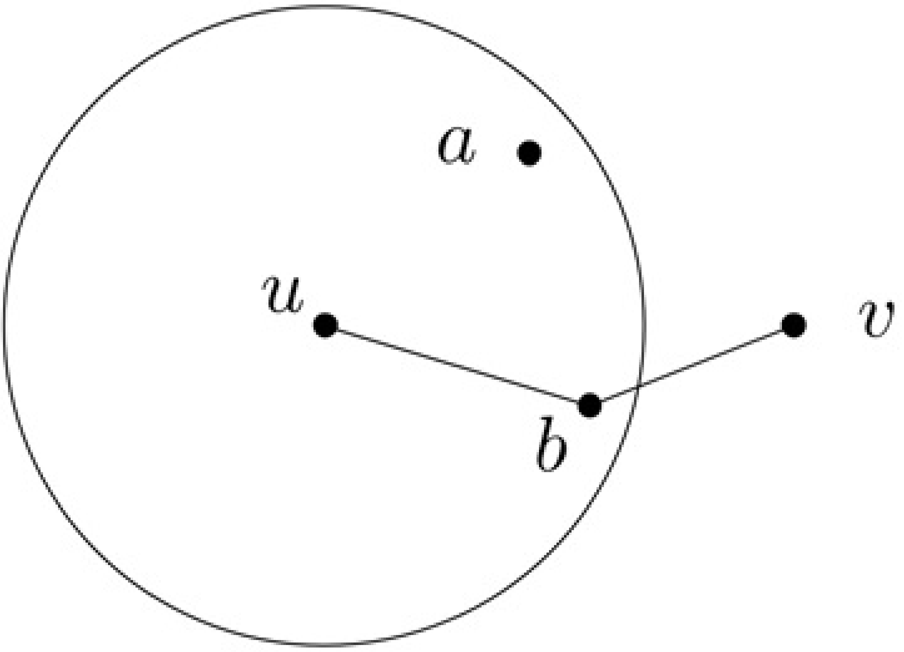


FIGURE 2.2: Example for cooperative routing

Instead intra-cluster nodes cooperatively forward the data to next cluster-head. The protocols presented by Liu et. al. [76], Ge et. al. [41] and Zhou et. al. [121] do not support node mobility. In general, cooperative caching provides robustness for the data within a network.

Wireless networks consisting of low power transmission links like MWSNs need a approach different than the traditional one. The traditional approach works with an assumption that a pair of node is either connected or disconnected and precomputes the routes. MWSN being highly dynamic due to node movements, such proactive routing is not suitable as computed routes become invalid. Traditional reactive routing approaches like in AODV [91] or location-based routing like IGF [16], EBGR [118], adapt to node mobility compared to proactive routing but are not robust against link failures. Traditional methods do not exploit two important characteristics for better design of routing protocol given below:

- Broadcast nature of wireless communications.
- Capability of nodes, other than the selected relay node, present in the neighbourhood.

Cooperative routing approach takes benefit of the above characteristics, but do compute the path before the packet is forwarded. Most of the cooperative routing protocols are designed for static networks to mitigate packet loss due to selected link failure. Cooperative caching in RRP [49] handles node mobility and is also robust against link failures. However, RRP requires pre-computation of path which needs to be done frequently in MWSNs, as the hops along the path may not be reachable due to mobility. So a routing strategy that selects a path for each packet independently would have an ability to counter-attack the effects of mobility. The link unreliability in MWSNs can be handled using opportunistic routing which explores spatial and temporal diversity. The next section presents brief explanation and review of opportunistic routing.

2.5 Review of Opportunistic Routing Protocols

Opportunistic routing (OR) is a non-deterministic routing strategy proposed for efficient handling link failures in wireless networks. In traditional routing, each node checks the linked nodes and determines a path from source to destination based on route metric. On the other hand, in OR protocols node having data, broadcasts the packet to set of nodes called as candidate relay set (CRS). All the member nodes of CRS will run a forwarding agreement, to decide which node in CRS should forward the packet. Other members of CRS withdraw themselves from forwarding the packet. The Figure 2.3(a) illustrates how traditional routing forwards the packet by determining path from node A to node G. The packet originated from node A follows a path $A - C - D - G$. In Figure 2.3(b) node 1 wants to deliver the packet node 10 using opportunistic routing. Node 1 broadcasts the packet, which is heard by node 2, 3, 5, 4 and 6. These nodes form a CRS and execute a forwarding agreement to decide that node 6 should forward the data. The subsequent nodes follow the same approach till the data reaches the destination.

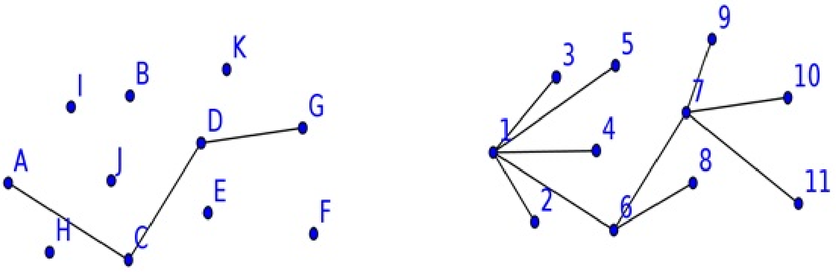


FIGURE 2.3: (a) Traditional routing (b) Opportunistic routing

The term *opportunistic* means that there exist a possibility that every node in WBA [109] can receive a packet and has equal potential to contend for being relay node. OR strategy broadcasts the packet to all its neighbours with an optimism that atleast one node amongst the neighbours receives the packet. The probability that atleast one of the neighbour receiving the packet is very much higher compared to probability of specific sensor device receiving the packet followed in traditional routing.

The Figure 2.4 illustrates the how probability of successful reception is increased in OR compared to traditional routing. Every link in the network has probability of

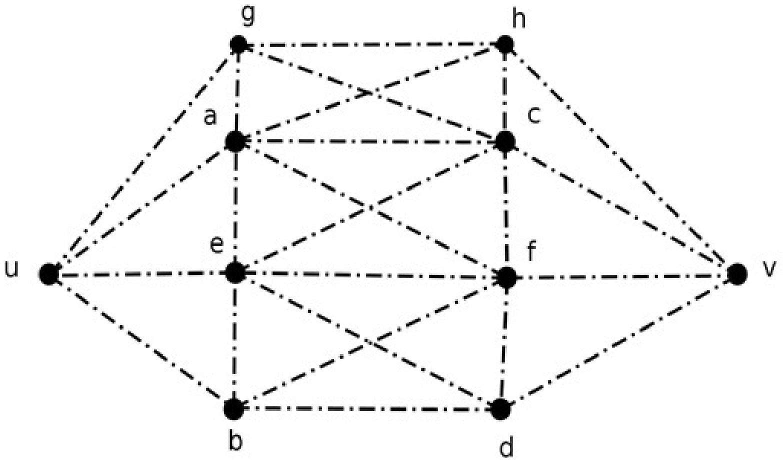


FIGURE 2.4: Example of OR. Each link has delivery probability of 0.4

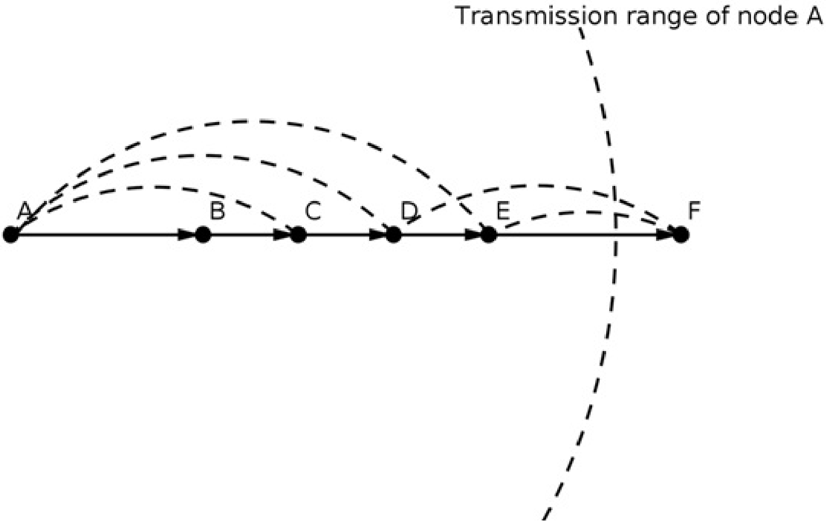


FIGURE 2.5: Spatial diversity and OR

successful packet delivery equal to 0.4. As shown in the Figure 2.4, suppose node u is the source and wants to send a packet to node v. In traditional routing node u will select a relay node a-priori. Therefore the probability that the packet is not received or is lost i.e. necessity of retransmission of the packet in traditional routing is $1-0.4 = 0.6$. In OR, node u will broadcast the packet to the members of CRS i.e. nodes g, a, e and b. The likelihood of atleast a single node in the CRS receives the packet successfully is calculated as $(1 - (1 - 0.4)^4) = 0.8704$. The probability that none of the node in CRS will receive the packet is 0.1296 which is much lower than 0.6. The OR strategy exploits the spatial diversity in densely deployed MWSNs as illustrated in Figure 2.5. Node A broadcasts the packet and OR strategy relies on chance that nodes B, C, D and E hear the packet. Node F is in the transmission range of both node D and E. If node E acts as relay than node D should be informed about the same so that it inhibits itself from transmitting the packet. The dark edges in Figure 2.5 show the path between nodes A to F for traditional routing.

OR offers following advantages for routing the data

- Increased reliability: As the packet is transmitted using any one of the available links, the probability of successful transmission is increased.
- Increased distance: OR follows broadcast, so link of all quality and distance are considered during a single transmission. There exist a chance that longest relay receives the packet at the same transmission power level, which also adds to energy savings.

Selection diversity (SD) based routing proposed by Larrson [63], Larsson and Johansson [64] dynamically selects only one relay node amongst the collection of potential relay nodes before the transmission of packet and OR selects after the packet is broadcast [19]. Table 2.2 shows the comparison of selection diversity and OR routing strategy.

In OR, it is important to maintain CRS as well as forwarding agreement. The CRS may be local or global depending on the routing algorithm. Selecting a relay node within a CRS requires node ordering and node elimination. Node ordering is preferably done using route metrics like hop-count, link status, expected transmission time (ETT) [32], expected number of transmission (ETX) [34], expected anypath transmission (EAX) [119], expected anypath transmission time (EATT) [65] etc. Location based opportunistic routing protocols for example Zeng et. al.[116], Kai Zeng et. al.[117] and Zubow et. al. [123] use energy as metric. Energy per advancement (EPA) is the metric used in energy constrained networks. Extreme opportunistic routing (ExOR) [15], MAC-independent OR and Encoding (MORE) [22], economy [48] and simple opportunistic adaptive routing (SOAR) [99] use ETX as metric for node ordering.

Type of Routing	Nature of Transmission	Selection of Relay node	Potential Relay Nodes	Nature of Relay Selection
Opportunistic Routing	Broadcast	Post-packet transmission	All the neighbourhood nodes	Dynamic
Selection Diversity	Unicast	Pre-packet transmission	All the neighbourhood nodes	Dynamic
Traditional Routing	Unicast	Pre-packet transmission	Single	Static

TABLE 2.2: Comparison of Routing Strategies

2.5.1 Cost Calculation in Opportunistic Routing

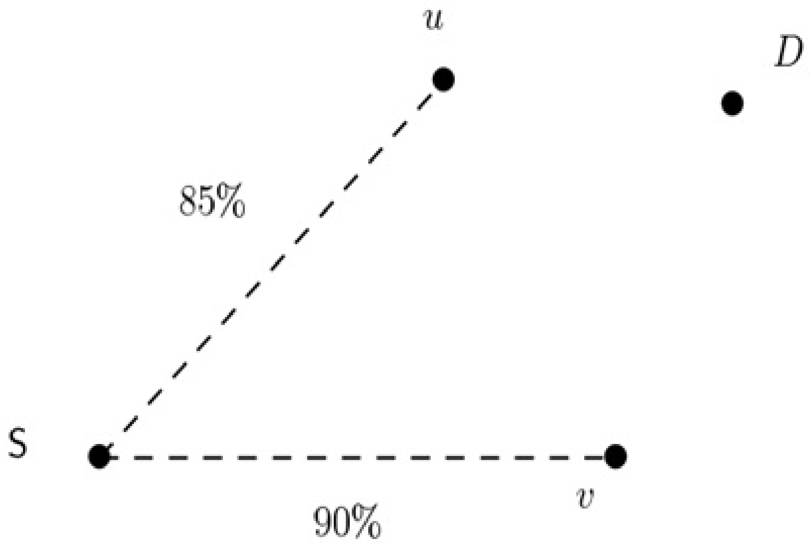


FIGURE 2.6: Cost calculation in OR

The cost incurred for successful delivery of packet to destination D is calculated as cost of sending a packet from source S to CRS and expected cost of forwarding from CRS to D. The Figure 2.6 illustrates how the cost of forwarding is calculated in OR. Let node u and v form a CRS u, v as they are connected to S and node ordering list (v, u) as node u is closer to destination D compared to node v. EAX can be determined as reciprocal of probability that alteast one of u, v will receive the packet sent by S as shown in Equation 2.1. The labels 85% and 90% indicate successful delivery probability for the edges (S, u) and (S, v) respectively. EATT product of packet transmission time and EAX as shown in Equation 2.2. Out of the total packets transmitted, node v forwards $\frac{0.9}{[1-((1-0.9)(1-0.85))]}$ number of packets and $((1 - 0.9) \times 0.85)$ are forwarded by node u. Therefore the cost $C(u, v, D)$ is calculated as shown Equation 2.3.

$$EAX = \frac{1}{[1 - ((1 - 0.9)(1 - 0.85))]} \tag{2.1}$$

$$EATT = PTT \times EAX = \frac{packetsize}{bitrate \times [1 - ((1 - 0.9)(1 - 0.85))]} \tag{2.2}$$

$$\begin{aligned} C(u, v, D) &= AverageC(v, D) + AverageC(u, D) \\ &= EAX \times 0.9 \times Cost(v, D) + EAX \times (1 - 0.9) \times 0.85 \times Cost(u, D) \\ &= \frac{0.9 \times Cost(v,D) + (1-0.9) \times 0.85 \times Cost(u,D)}{[1-((1-0.9)(1-0.85))]} \end{aligned} \tag{2.3}$$

Node elimination is necessary for removing the nodes that would affect the performance of OR. Higher number of nodes in CRS increases overhead as CRS may be part of packet header. Including nodes that cannot hear each other increase the chances of duplicate transmissions. Following are some the metrics used for node elimination

- Node connectivity : SOAR [99] and economy [48].
- Virtual link strength: SOAR.
- Duplicate Probability: Zubow et. al.[123], Qiang et. al. [96] on a predefined candidate order.

- Pruning: Koutsonkolas et. al. [60], Chachulski [22] on a predefined candidate order.

Forwarding agreement is used to ensure coordination among the nodes in CRS. Such coordination helps in deciding whether a node should transmit the overheard packet or not. A good forwarding agreement should completely avoid the duplicate transmissions at the smallest cost possible. Forwarding agreement among the nodes can be achieved using timer, token or network coding. Timer based agreement assigns a pre-defined delay to the nodes in the node ordering. Such mechanism is used in Biswas and Morris [15], Rozner et. al. [99] and Zeng et. al. [117]. The delay mechanism ensures that a node becomes opportunistic only if the every higher priority node fail to relay the packet. Timer-based forwarding agreement cannot completely avoid duplicate transmissions. Destination node generates a token which flows to connected nodes till it reaches the source. Token-based agreement is observed in Economy [48] protocol. In this mechanism all the nodes in CRS collect the overheard packet but can transmit the packet only if it possesses a token. Each of the relay nodes caches the packets to be sent and unacknowledged packets. The token contains the acknowledgement for packets. Token-based mechanism has drawbacks like cost of token packets and relay nodes will remain idle for unavailability of token. Network coding based forwarding agreements involves use of code and decode flows of packet. MORE [22] implements this strategy for forwarding agreement.

In this paragraph a brief review of different opportunistic routing protocols is presented. Table 2.3 summarizes the review of OR protocols. Contention based forwarding (CBF) [40] is one of the earliest OR protocol bur not designed and evaluated for WSNs. EXOR [15] can be termed as the first OR scheme which uses batch-limit mechanism for forwarding agreement. The performance of ExOR is better than traditional routing but it cannot avoid duplicate transmissions. MORE [22] uses network coding for forwarding agreement. There are no acknowledgements for received packets in MORE as well as it suffers from redundant packets. CodeOR [70], SlideOR [71] and CCACK [60] are other network coding based routing algorithms. SOAR [99]uses timer-based forwarding agreement in which CRS is prepared at source as well as relay nodes. SOAR has better transmission control and duplicate packet avoidance compared to ExOR. Economy [48] is another OR protocol which is free from duplicate packets. The absence of packet duplicates helps to minimize

Protocol	Batch	Forwarding Agreement	Local or Global CRS	CRS Metric	Node elimination
CBF	No	Timer (Local)	Local	Geographic distance	NA
ExOR	Yes	Timer (Global)	Global	ETX	Pruning
SOAR	No	Timer (Local)	Both	ETX	Virtual link quality Node connectivity
MORE	Yes	Network coding	Global	ETX	Pruning
Economy	No	Token	Local	ETX	Node Connectivity
GOR	No	Token	Local	Coordination overhead and geographic distance	NA

Table 2.3: Summary of Review of OR protocols

the number of transmissions to deliver the packet to the destination compared to ExOR. Economy protocol implements token-based mechanism for forwarding agreement. GOR [116], [117] prepares a CRS using local information i.e. neighbourhood nodes. GOR has limitation of duplicate transmissions induced due to timer-based forwarding mechanism. The challenges and open issues for research in OR include forwarding agreement, calculating expected cost of forwarding, robustness and transmit power control.

	Node Mobility Supported	Node Mobility Not Supported
Robustness Provided	ZRP, gossiping, TBRPF, SPIN and RRP	PEGASIS, APTEEN, TTDD HPAR, Liu et. al.„ Ge et. al. And Zhou et. al.
Robustness Not Provided	TORA, E-TORA, DD, ACQUIRE, GEAR, DREAM, IGF, PAGER-M, EBGR, AODV, CBF, ExOR, SOAR, MORE, EEOR, economy and GOR	LEACH, TEEN and COUGAR

Table 2.4: Review of protocols with node mobility support and robustness

The capability of protocols reviewed to support node mobility and provide robustness is summarised and presented using Table 2.4. The summary is based on whether the protocol supports node mobility or not and provides robustness or not.

2.6 Conclusion

Thus, this chapter presents a brief review of routing protocols for MWSNs. The feasibility of using MANET protocols for data forwarding in MWSNs is discussed and it is observed that these protocols are generally not suitable for routing in MWSNs due to characteristic differences among the two networks. Routing protocols in large number are proposed for WSNs in recent years, but majority them are designed for static networks. Classifications of routing protocols along-with characteristics of each class of protocols are briefly discussed. The routing protocols proposed for WSNs are investigated with focus towards their support for node mobility and robustness. Subsequently, a brief review of cooperative routing strategies along with brief review and comparison of opportunistic routing protocols are presented.

To summarize further, it can be observed that the traditional routing strategies do not have ability to effectively handle effect of node mobility in data packet routing. The dynamic topology of MWSNs makes the routes invalid more frequently compared to the static networks. In case of MWSNs, traditional repeated route computations increase network overheads and energy consumption. Cooperative routing provides robustness to an established path through mechanism of cooperative caching. In general, the routing protocols that pre-define the routing path before forwarding the packet are generally not suitable for dynamic WSNs. Rather non-deterministic routing strategies in which the path or next relay is determined after the packet is being broadcast are more suitable in mobile environments. Opportunistic routing strategies define the routes after transmission of packet and respond positively to node mobility. OR is not difficult for implementation due to broadcast nature of wireless communication. ExOR, MORE, SOAR and economy are the most notable works in OR. The existing OR protocols need further improvements to minimize energy consumption, routing overheads and ensure robustness.

Data routing and route selection are the most vital activities in MWSNs and there exist a scope for further improvements in routing mechanism that will be suitable in node mobility scenario with reduced overheads, minimized energy requirements and will also enhance robustness.

Mobility being most important for dynamic WSNs, the next chapter presents concepts on synthesising node mobility and its performance on MWSNs.

Chapter 3

Mobility in WSN: Models and their Performance Assessment

This chapter includes a brief discussion on various mobility models used to model the mobility characteristics of MWSN, alongwith study of MWSN performance under different conditions like node scalability and varying mobile speed.The objective behind this study are

1. To study how different mobility models synthesize mobility of nodes for MWSNs.
2. To study effect on key performance parameters of MWSN using different mobility models by varying the node density and node movement speeds.
3. To understand the impact of node mobility on performance of MWSNs.

For the above simulations, a well-known routing protocol Ad-hoc on-demand distance vector (AODV) [91] is used, just to get better understanding of various performance parameters and their correlations with different types of mobilities in MWSNs. This, however, would not have any effect on design issues of energy-efficient routing protocol discussed in the following two chapters.

Nodes in mobile networks undergo change in acceleration, velocity, direction and location during their movements. All these characteristics of node movement are compositely expressed as a mobility model [10]. While designing the routing protocol for infrastructure-less mobile networks, it is important to investigate the relation between mobility models and performance of MWSNs. In simulation environment, such model should emulate the node movement pattern similar to the node movements in targeted real application. To capture realistic node movements, it is ideally expected that the mobility model should be designed on the basis of node movement traces in application environment [108]. Synthetic models have been used for describing movements of the node in simulations. Obtaining precise trace of node movement using a MWSN deployed in a field is a challenge. Bai and Helmy [10], Camp et. al. [20] present a review of various models used for synthesising the node movement. In MWSNs, it is necessary to record location, speed and direction of a moving node at micro-level as these factors directly influence breaking and formation of the links with the neighbourhood nodes. In ad-hoc networks, based on the application, the nodes may move independently or in a group. In Some applications, the node mobility is influenced by movement history. To synthesize mobility for ad-hoc networks various models have been proposed in the literature as illustrated in Figure 3.1. Mobility for MWSN applications like habitat monitoring, in which each node moves independently can be modelled using entity models. Mobility in applications that involve collective movement of sensor nodes, like cattle herd monitoring, military troop movement etc. can be simulated using group mobility models. In this study, the applications that require random node deployment and movements independent of each other are considered, in which the mobility can be simulated using entity models. In this chapter, a study investigating the effect of first four entity mobility models and resulting performance of MWSN are discussed. In the following paragraph some of the entity mobility models are briefly described followed by simulation parameters and results

3.1 Mobility Models

3.1.1 Random Waypoint Mobility Model (RWMM)

In all the random based mobility models, the mobile nodes move randomly by selecting its destination, speed and direction independent of neighbour nodes. Johnson

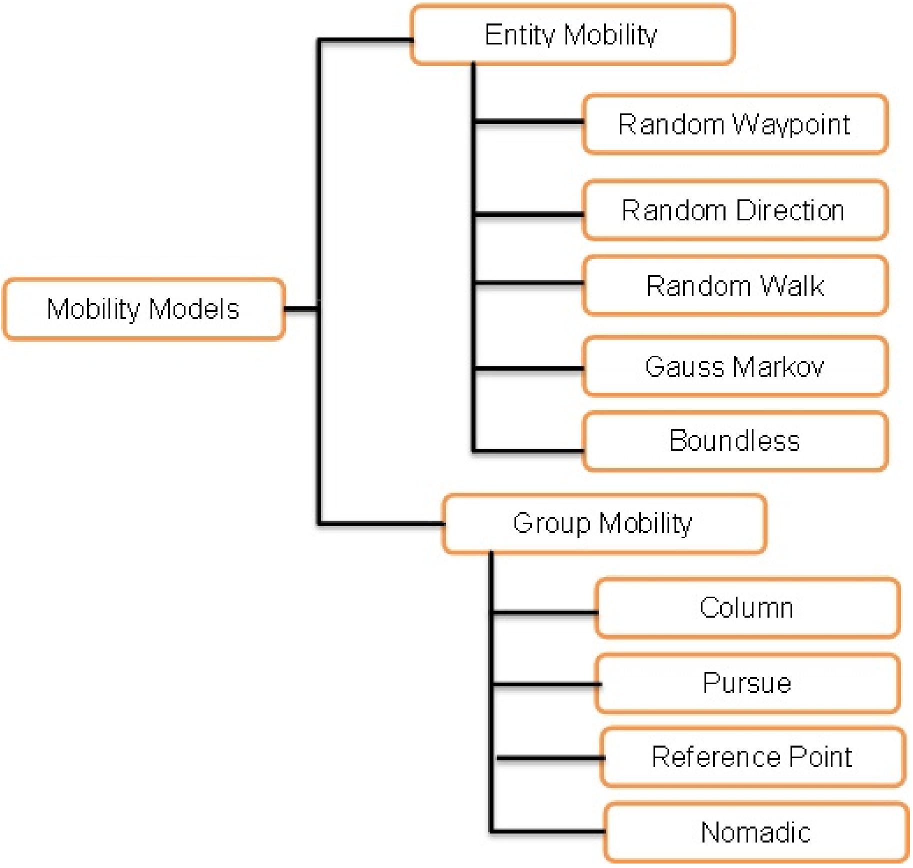


FIGURE 3.1: Random and group mobility models

and Maltz [57] proposed the random waypoint mobility model (RWMM) which is widely used by many researchers to synthesize mobility of nodes in ad-hoc networks. In this model, a node waits for period defined as pause time, denoted by t_p, between two successive movements. Initially, each mobile node waits for pause time and then randomly selects a destination location. A node travels across the area at a random speed distributed uniformly from v_0 to v_{max}, where v_0 and v_{max} represent the minimum and maximum node velocities. A node performs the above steps until the simulation ends. A dynamic network can be simulated using RWMM if the velocity is close to maximum and the pause time is minimum. A typical node movement pattern is shown in Figure 3.2. When the pause time is zero, the movement pattern generated is similar Random walk mobility model (RWkMM). RWMM causes gathering of nodes in one region of field being monitored, termed as dense waves [18].

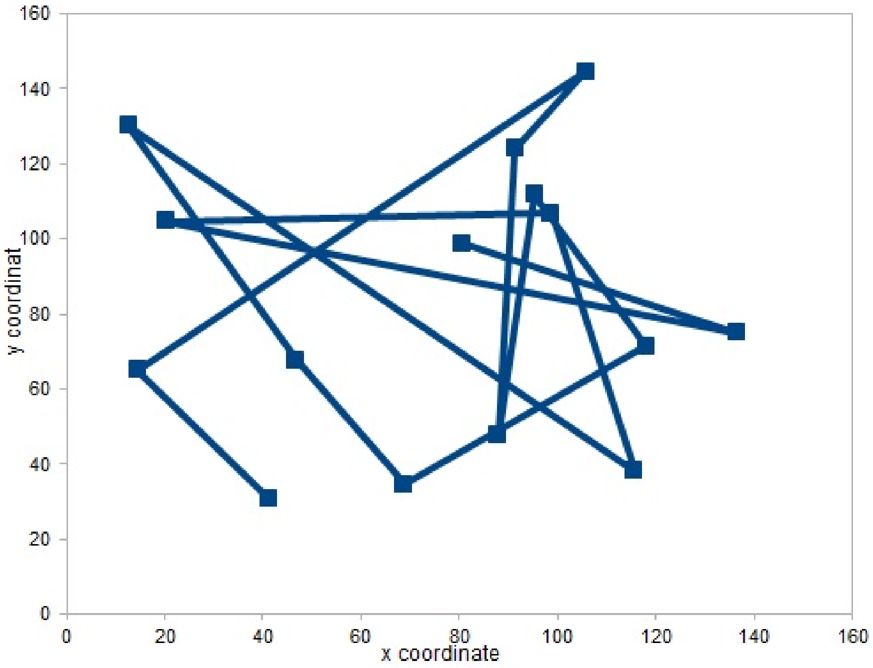


Figure 3.2: Node mobility pattern for RWMM

3.1.2 Random Direction Mobility Model (RDMM)

Random direction mobility model (RDMM) [98] is designed to avoid dense waves phenomenon indicated above in RWMM. Nodes choose a random direction and tend to move towards the interior part of the simulation area until the subsequent location in that direction or area limits are reached as shown in Figure 3.3. At the start of simulation, every node is initialised with an angular direction of movement in the range $0 - 2\pi$ and random speed between minimum and maximum velocity. The nodes are placed randomly in the field. When the node reaches the subsequent position or the boundary, it stops until the pause time expires and then selects a new random value of velocity and direction within the range. As the nodes tend to reach the boundary and subsequently pause the movement, it increases the inter-node distance as well as average number of hop counts required for data forwarding, which results in higher energy consumption. As may be seen in Figure 3.3, it also creates low node density region in the vicinity of central part of the network giving rise to possible increase in loss of connectivity in MWSN.

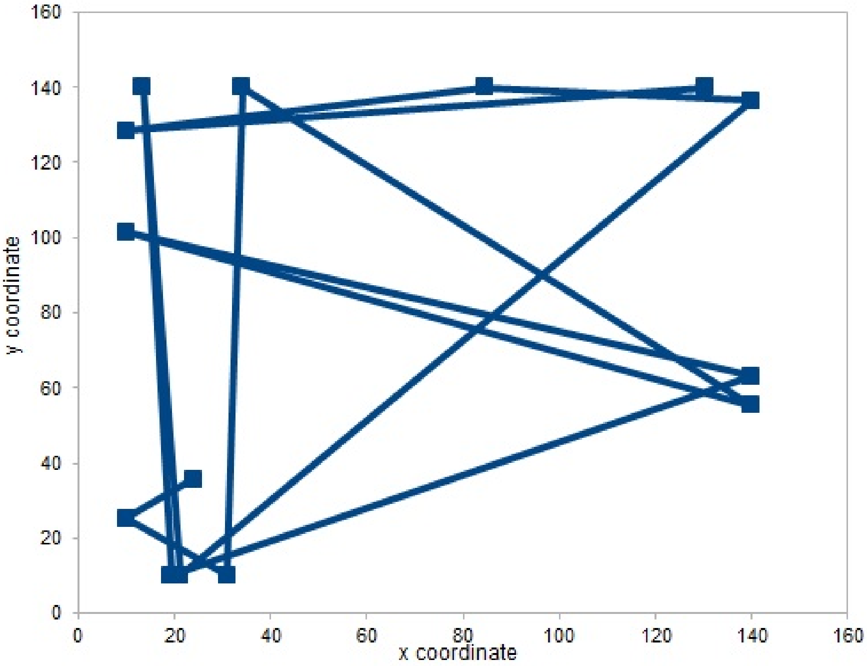


FIGURE 3.3: Node mobility pattern for RDMM

3.1.3 Random Walk Mobility Model (RWkMM)

Random walk mobility model (RWkMM) works using distance or time as input and avoids concentration of nodes in one region . Each move of the node is independent of the previous move. To perform movement to new location, a node selects a random speed in between the minimum and maximum velocity values and random angle in the limits $[0 - 2\pi]$. The node moves for fixed time period defined as configuration parameter while synthesising the node movements. Instead of fix time, the model can be used with fixed distance per movement. During the movement, if the node strikes the area boundary than node reflects back within the monitoring area by choosing a random angle for new direction. A RWkMM movement pattern for a typical node with fixed time as parameter is shown in Figure 3.4. For small values of distance or time, Brownian motion is generated. If the values of time or distance is large then movements are similar to RWMM [20].

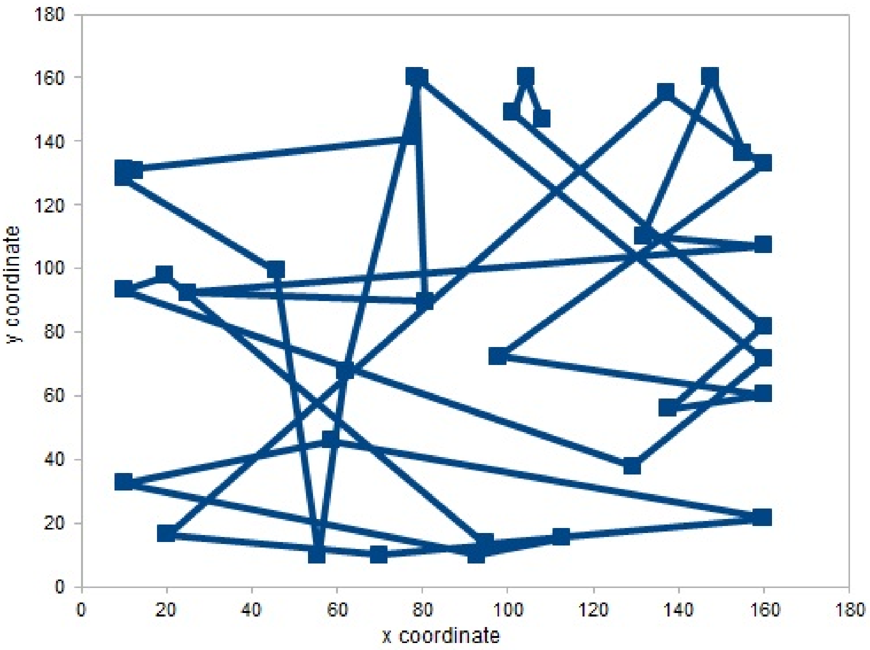


FIGURE 3.4: Node mobility pattern for RWkMM

3.1.4 Gauss Markov Mobility Model (GMMM)

Liang and Hass [68] developed the Gauss-Markov mobility model (GMMM) for personal communication system networks. A tuning parameter α with an appropriate value in the interval $[0, 1]$ is used to have movements close to realistic application [20]. The next movement speed and direction depends on the previous movement as shown in Equation 3.1. v_{n-1} and d_{n-1} are the previous movements speed and direction. $\bar{v}$ and $\bar{d}$ are mean values of speed and direction. $v_{X_{n-1}}$ and $d_{X_{n-1}}$ are Gaussian variables for speed and direction. A typical node movement for GMMM is shown in Figure 3.5. For two extreme values of α GMMM shows a specific behaviour. When $\alpha = 0$, GMMM is same as RWkMM. When $\alpha = 1$, GMMM as high correlation with the previous speed and direction resembling fluid flow mobility model. In our simulations we have considered $\alpha = 0.5$.

$$\begin{aligned} v_n &= \alpha v_{n-1} + (1-\alpha)\bar{v} + \sqrt{(1-\alpha)^2} v_{X_{n-1}} \\ d_n &= \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha)^2} d_{X_{n-1}} \end{aligned} \tag{3.1}$$

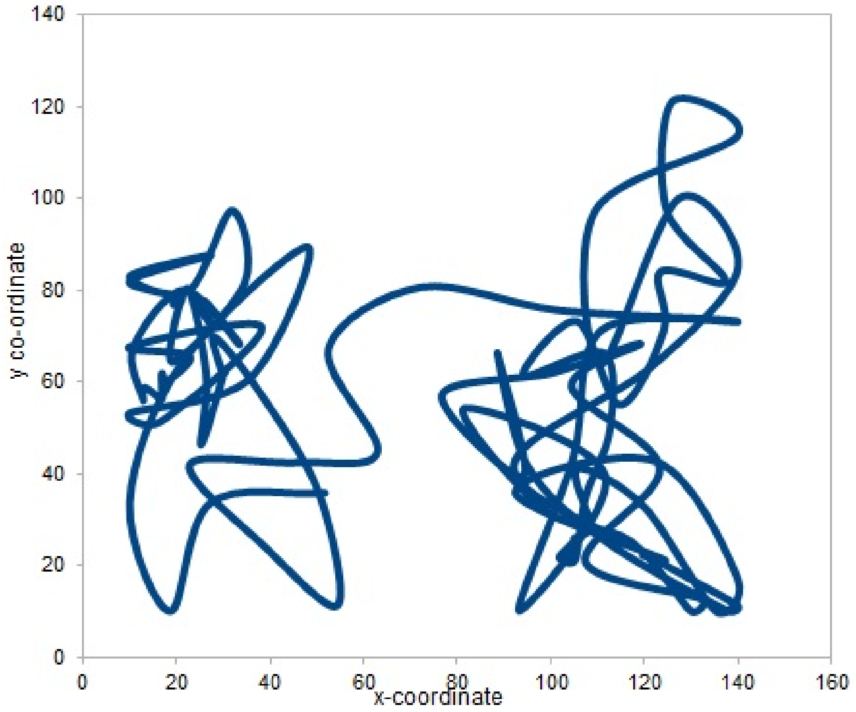


FIGURE 3.5: Node mobility pattern for GMMM

3.2 Performance Metrics

The response of chosen AODV [91] routing protocol using various mobility models in MWSN is evaluated using following performance metrics. Throughput, packet delivery function and average end-to-end delay [54] are defined as per the Equation 3.2, Equation 3.3 and Equation 3.4 respectively.

1. **Throughput**:

$$Throughput = \frac{N_{pr} \times P_s \times 8}{T_s \times 1000} \; kbps \tag{3.2}$$

   Where N_{pr}, P_s and T_s represent number of packets received, size of packet and simulation time respectively.

2. **Packet delivery function**:

$$pdf = \frac{N_{pr}}{\Sigma_{i=1}^{n} P_{sent_i}} \tag{3.3}$$

Where N_{pr}, P_{sent_i} and n represent number of packets received at sink, packets sent by sensor node i and number of sensor nodes respectively.

3. **Average end-to-end delay**:

$$\begin{aligned} D &= \frac{\Sigma_{i=1}^{N_{pr}} d_i}{N_{pr}} \\ &= \frac{\Sigma_{i=1}^{N_{pr}} (t_{r_i} - t_{s_i})}{N_{pr}} \end{aligned} \tag{3.4}$$

where d_i is the transmission delay of packet i.

4. **Residual Energy**: Packet sending and receiving are the activities that require large amount of energy. The residual energy is the energy available with the node. The Equation 3.7 determines the average residual energy of a node denoted by $\bar{E_r}$ for a WSN with n devices. Higher the value of $\bar{E_r}$, higher will be the network lifetime. The energy consumed by each node denoted by E_c can be measured as given in Equation 3.5. A node requires energy for transmission or forwarding of packet. A node may originating the data for a packet and so will consume only the energy required for transmission. A node may act as relay for forwarding the packet, so it will require energy for reception and transmission.

$$E_c = \begin{cases} E_{Tx}, & \text{if the node is transmitter} \\ E_{Rx}, & \text{only receives data} \\ E_{Tx} + E_{Rx}, & \text{if the node acts as relay} \end{cases} \tag{3.5}$$

Let E_r denote the residual energy of a node. After transmitting or forwarding any packet i, the residual energy of the node is calculated using Equation 3.6

$$E_{r_i} = E_{r_{i-1}} - E_c \ Joules \tag{3.6}$$

$$\bar{E_r} = \frac{\Sigma_{j=1}^{n} E_{r_j}}{n} \tag{3.7}$$

5. **Routing Overhead**:It is defined as ratio of total routing packets exchanged denoted by P_{trtp} to total data packets received at sink denoted by N_{pr} as shown

in equation (3.6). The metric value will range in 0 to 1. For better performance the value should be as small as possible.

$$ro = \frac{P_{trtp}}{N_{pr}} \tag{3.8}$$

6. **Packet Drops**: It is defined as ratio of number of packets dropped N_{pd} to total number of packets sent in the network consisting of n nodes.

$$Drop = \frac{N_{pd}}{\Sigma_{i=1}^{n} P_{sent_i}} \tag{3.9}$$

3.3 Simulation and Results Discussion

WSN simulations are done using Network Simulator 2 (NS2) [52]. The simulations are carried over area of $150m \times 150m$, for time period of 200 seconds. Each sensor node transmits the packet at an interval of 5 seconds. The simulations are done with AODV [91] routing protocol by using various entity mobility models discussed in Section 3.1. The sink is assumed to be stationary and placed at the center of simulation area. The sensor node deployment is considered random over the geographical area for simulation. Considering the simulation area to be fixed, the total number of sensor nodes is varied. Four specific cases, one representing low node density i.e. 36 sensor nodes, two cases representing medium node density i.e. 72 and 108 sensor nodes and one case of relatively higher node density i.e. 144 sensor nodes are considered for simulation and performance evaluation. For each of the case mentioned above, three speeds viz. $0.5m/s$, $1m/s$ and $1.5m/s$ are considered for node movement. The results calculated are based on average of 20 trials of simulation, with each simulation run having total random initial deployment of nodes. Subsequently, the node movements are defined as per the mobility models discussed in Section 3.1. The simulation parameters are shown in Table 3.1.

3.3.1 Results and Discussion

1. **Throughput**

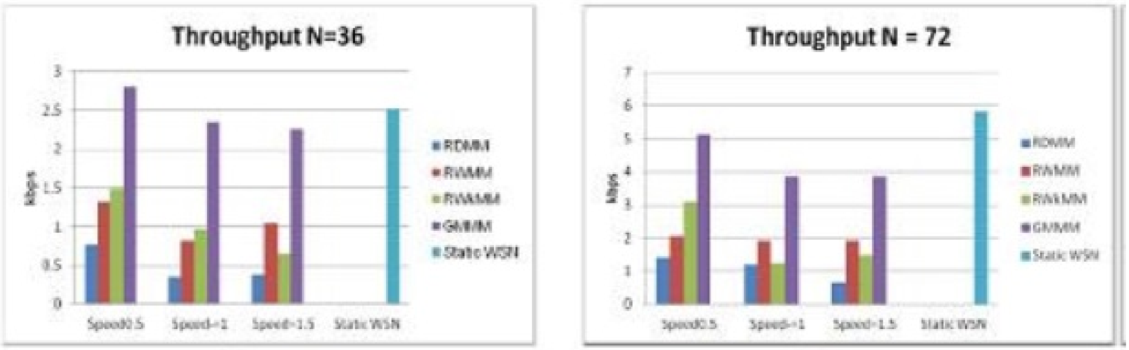
Parameter	Value
Number of nodes	36, 72, 108 and 144
Speed	$0.5, 1, 1.5 m/s$
Initial Energy	$10 Joules$
Transmit Power	$0.036W$
Receive Power	$0.024Ws$
Simulation Time	$200 seconds$
Simulation Area	$150 \times 150\, m^2$

Table 3.1: Simulation Parameters

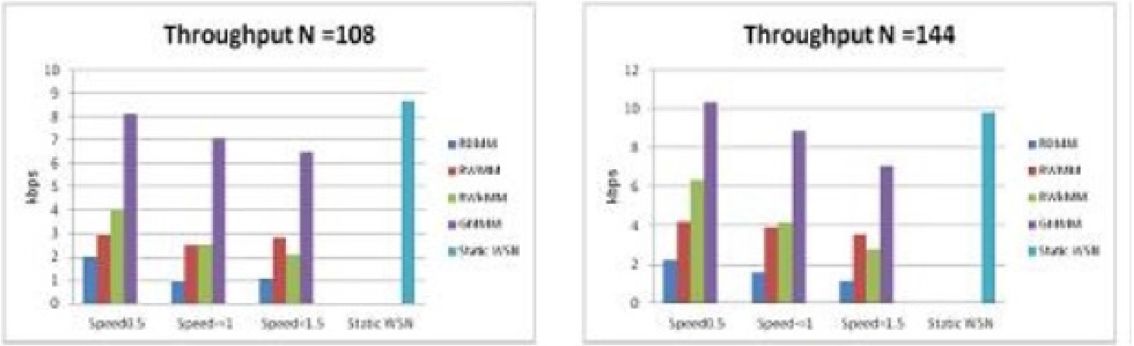
The results for throughput for various simulation scenarios are shown in Figure 3.6. For comparison sake we have also included results of static WSN. It is observed that, the throughput increases with decrease in speed. At a given node density, throughput is maximum for GMMM [68] and minimum for RDMM[98] for all speeds. For RDMM, this may be attributed to nodes located towards the boundary region. At a given speed, throughput increases with increase in node density, which is expected result. The performance of RWMM [57] and RWkMM is between the two extremes. It is observed that for lower node density and low speeds the throughput for GMMM is comparable with static WSN, whereas for all other mobility models some definite degradation is observed with respect to static WSN. This degradation significantly increases with increase in speed of node movement. At $0.5m/s$ and number of nodes equal to 36, GMMM gives marginally better performance than static WSN which may be attributed to the network being more connected due to node movements compared stationary random placement of nodes.

2. **Packet Delivery Function**

The simulation results for packet delivery function are shown in Figure 3.7. It can be seen that the *pdf* value is better at lower speeds as against *pdf* value at higher speeds, which is expected result. It is also observed that,



(a) N=36 (b) N=72



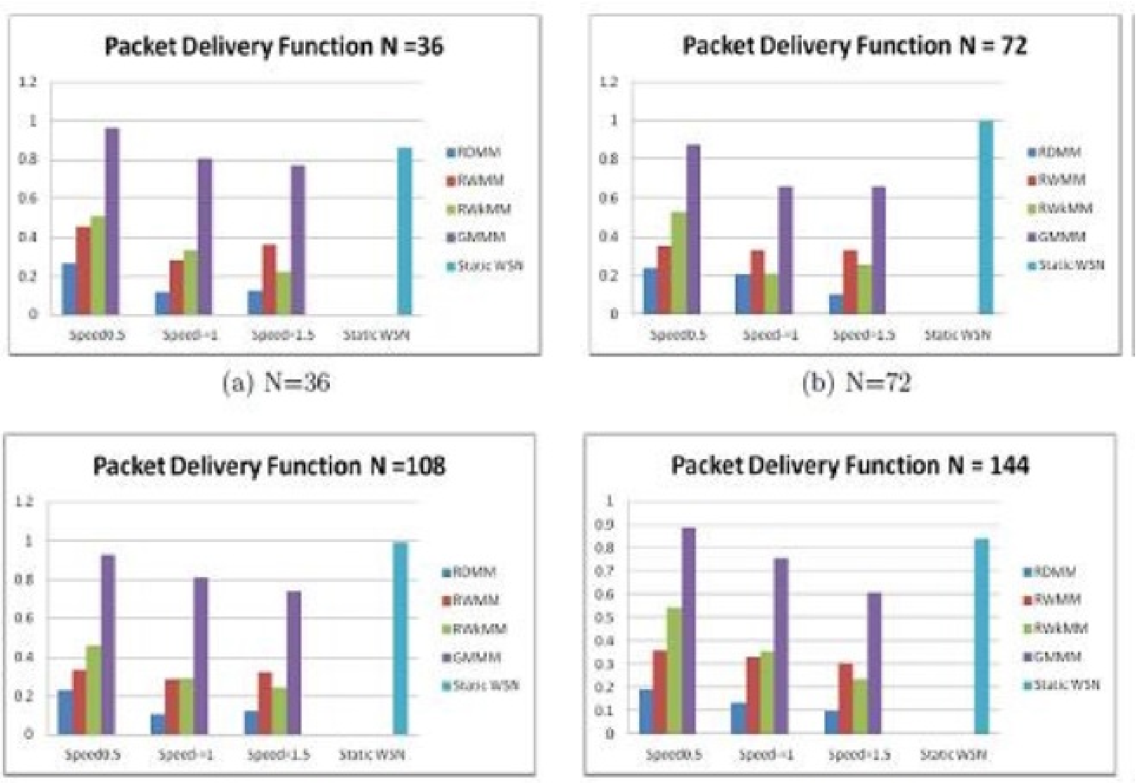
(c) N=108 (d) N=144

FIGURE 3.6: Results for throughput

GMMM gives higher *pdf* value and RDMM [98] gives lower *pdf* compared to other mobility models. This may be due to true randomness achieved in GMMM [68], which increases the probability of mobile nodes coming closer to sink. The performance of RWMM [57] and RWkMM lies in between the two extremes. Comparing the performance with static WSN, it is noted that there is performance degradation in *pdf* value for all the mobility models, at higher node density which is a expected result. However this degradation is marginal for GMMM. In fact, for lower speeds and lower node densities, GMMM exhibits marginally better performance compared to static WSN. This may be due to higher connectivity probability, observed in GMMM.

3. **Average End-to-End Delay**

The results for average end-to-end delay are shown in Figure 3.8. It is observed that average end-to-end delay increases with increase in number of nodes at all speeds. It is also observed that GMMM [68] shows lowest value of end to end delay and RDMM [98] shows highest value, compared to all other mobility



(a) N=36 (b) N=72

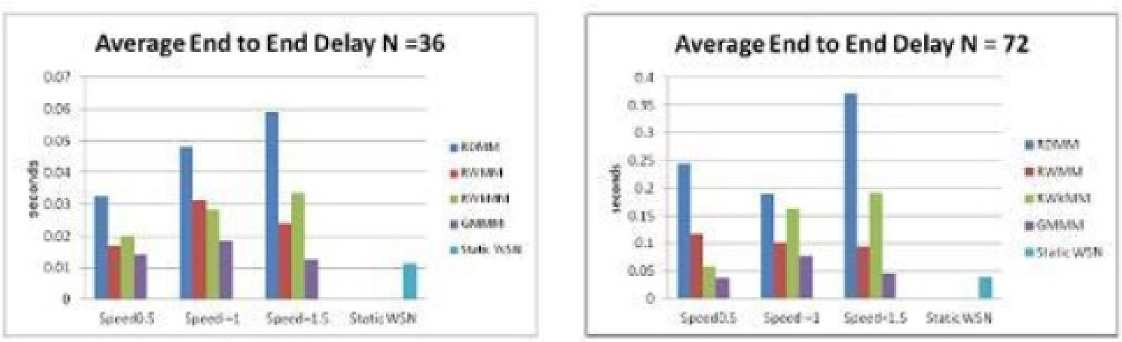
(c) N=108 (d) N=144

Figure 3.7: Results for packet delivery function

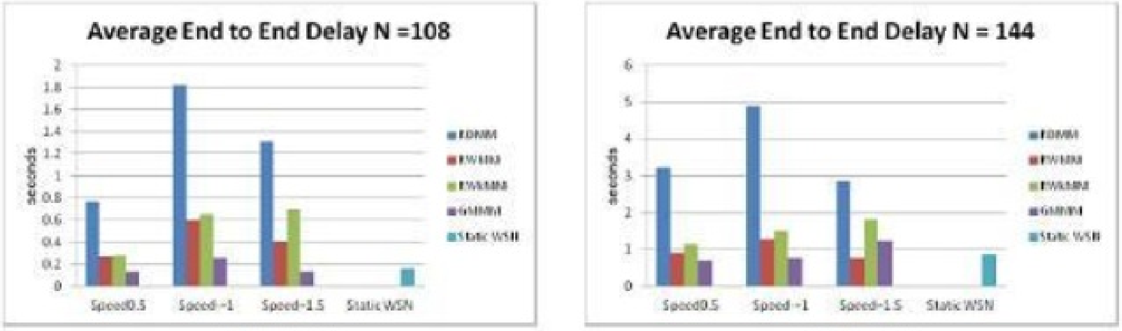
models, which are expected results. The performance of RWMM and RWkMM is in between the two extremes. Comparing the performance of all mobility models with static WSN, there is considerable degradation in end to end delay performance for mobility models RDMM, RWMM [57] and RWkMM, which is expected. For GMMM, the performance degradation is marginal.

4. **Residual Energy**

   The residual energy is measured as average of residual energy of all nodes, the results for which are shown in Figure 3.9. It is observed that average residual energy decreases with increase in node density for all mobility models at all speeds, which is expected result. The average residual energy for RDMM [98] and RWMM is comparable for low and medium node densities, for all speeds. But at higher node density RWMM shows better performance as compared to RDMM. GMMM shows considerable apparent degradation for average residual energy compared to all other mobility models as well as compared to static WSN. This degradation is marginal for RDMM and RWkMM. For RWMM



(a) N=36 (b) N=72



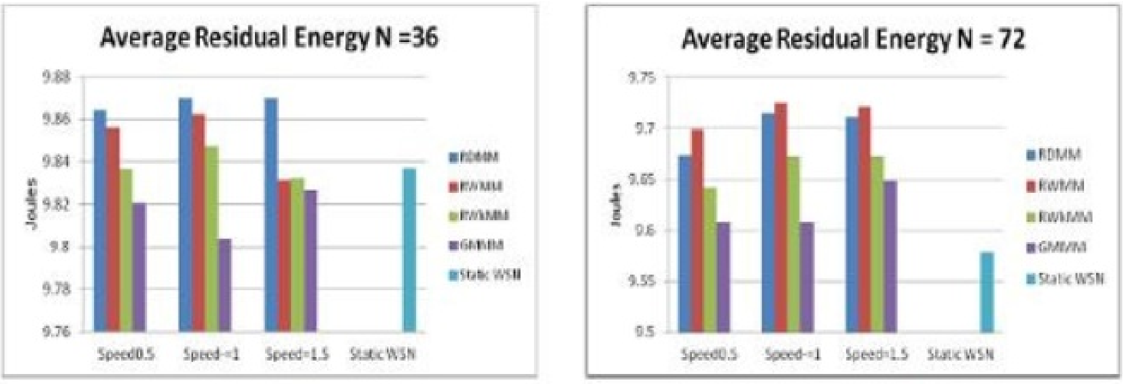
(c) N=108 (d) N=144

FIGURE 3.8: Results for average end-to-end delay

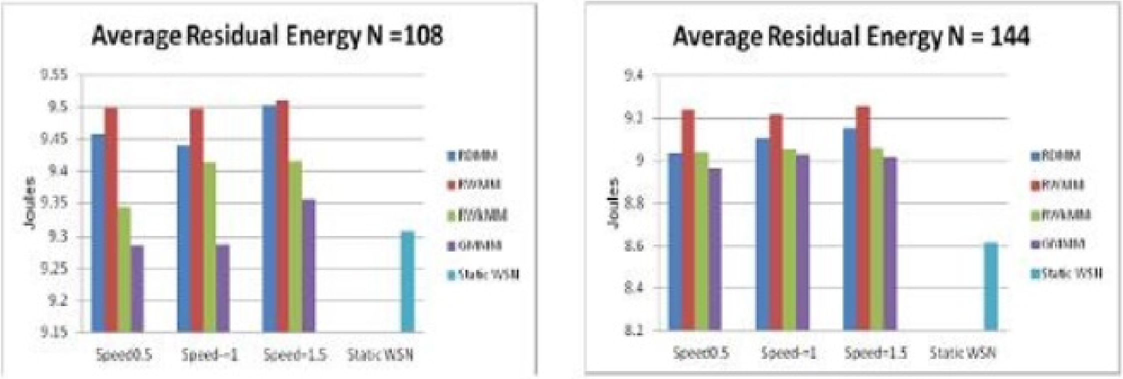
[57], it is observed that average residual energy is more compared to static WSN, which may be attributed to higher probability of nodes close to sinks, which considerably reduces demand on energy.

5. **Routing Overhead**

The results for routing overhead are shown in Figure 3.10. The routing overhead increases with increase in node density which is expected result for all models and for all speeds. RDMM shows higher routing overhead and GMMM [68] shows lowest routing overhead compared to other mobility models. For RDMM [98] this may be attributed to node locations near the boundary area. For GMMM, this may be attributed to true random movement of nodes. The performance RWMM and RWkMM is in between the two extremes. Comparing the performance with respect to static WSN, it is observed that routing overhead increases considerably for RDMM and RWkMM for all node densities at all speeds. The performance of RWMM [57] and RWkMM is comparable to static WSN for high node density and shows degradation at low node density.



(a) N=36 (b) N=72



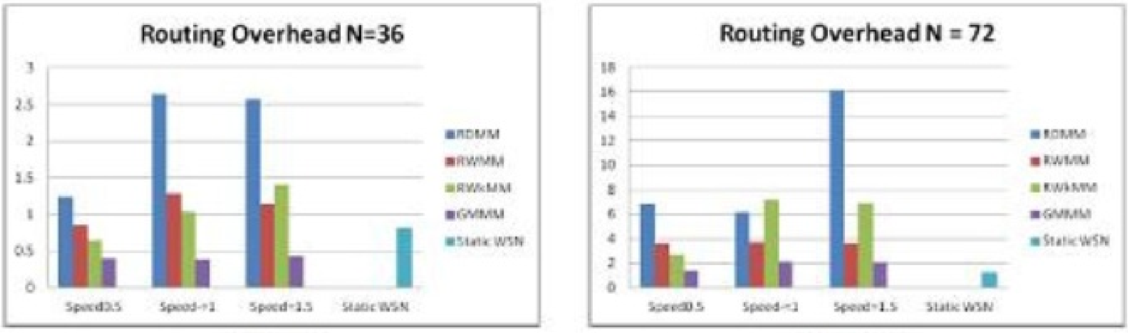
(c) N=108 (d) N=144

Figure 3.9: Results for residual energy

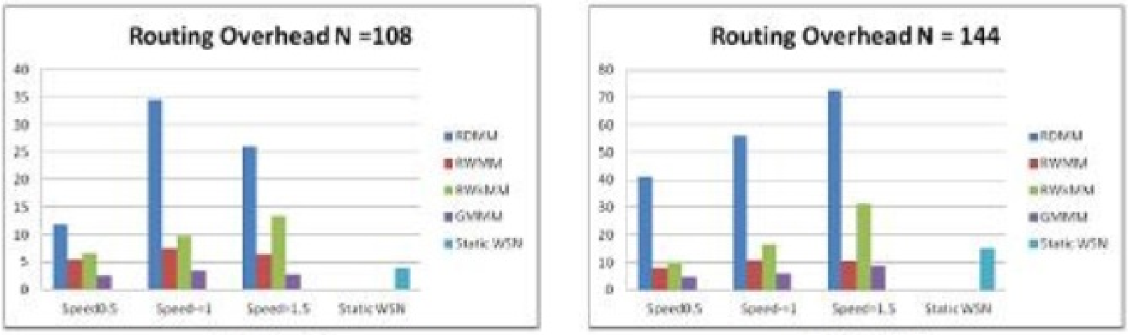
GMMM shows lowest routing overhead for low node densities and low speeds. The performance shows an improvement compared to static WSN, which may be due to higher connectivity probability in GMMM, explained above

3.4 Conclusion

The performance for various mobility models have been compared for different typical WSN speeds and node densities. It is observed that GMMM gives true random movement and exhibits better performance for throughput, packet delivery function, average end to end delay and routing overhead. GMMM appears to be better suited for simulating mobility very similar to mobility in real application. RDMM is not preferred as it increases the hop counts and also shows degraded performance for throughput, packet delivery and routing overhead. The performance of RWMM and



(a) N=36 (b) N=72



(c) N=108 (d) N=144

Figure 3.10: Results for routing overhead

RWkMM is comparable and is between the two extremes. It is observed in general that increase in the node mobility speeds degrades the MWSN performance, irrespective of choice of mobility model. Further, mobility model is chosen to synthesize mobility for fulfilling the requirements of different applications. However, choice of mobility does not have any impact on design philosophy of routing protocol. Thus, the objectives stated in the beginning of chapter to understand the correlation between node mobility and performance of MWSNs have been fulfilled in this study.

In Chapter 4 and Chapter 5, design and performance evaluation of CBEEOR and CCOF protocol is presented respectively. Even though GMMM models the node movement more realistically. However, it is not widely used by researchers thereby making the benchmarking difficult. Node movement while evaluating performance of CBEEOR and CCOF is simulated using RWMM which is extensively used by various researchers in the literature. This would also help in benchmarking the performance of the proposed protocols compared to other recent protocols published in the literature so far.

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[1] This work has been published and details are: Mandar Karyakarte, Anil S tavildar, Rajaesh Khanna, "Performance Evaluation of different mobility models for mobile wireless sensor networks using AODV", published in IJCNWMC ISSN 2250-1568. ISSN 2250-1568.

Chapter 4

Design and Simulation of Connectivity Based Energy Efficient Opportunistic Robust Routing

The chapter presents design and simulation of Connectivity Based Energy Efficient Opportunistic Robust (CBEEOR) routing protocol. Initially, a brief overview of opportunistic routing, especially for the two protocols namely, energy efficient opportunistic routing (EEOR) [82] and optimal opportunistic forwarding (OOF) [73] is given, as both of them are compared with CBEEOR for performance evaluation. Subsequently, the design of CBEEOR is discussed in detail. Lastly, a brief discussion on performance of CBEEOR in comparison with EEOR and OOF is presented.

4.1 Introduction

Routing is a process of selecting a path between the sender and receiver to transmit the data. The paths in intermittently connected networks are highly unstable and may break frequently [28]. The two essential requirements to design the routing protocol for MWSN are to minimize the energy cost and maximize the network throughput. As illustrated in Chapter 2, traditional routing discovers a path before the transmission of the packet. The discovery of the paths is carried using routing packets, which store the costs of the links. Using the cost information a path is selected and stored in each node as routing table, till the time routing protocol considers it to be stable. The traditional routing protocols assume the network to be connected and therefore react at a slow pace to dynamic changes like node failure, node movement, link quality etc. The opportunistic routing protocols dynamically decide the next hop node, when the packet is ready for the transmission. These protocols seek benefit of WBA [109] to elect the best next hop among the set of packet receptors. These protocols use cooperative caching, sharing and coordination of cached data among multiple nodes. Selecting the set of receptor nodes and prioritizing the receptors for forwarding the packet are key factors for the better performance of opportunistic routing protocols. In the following section a brief overview of opportunistic routing is discussed.

4.2 Overview of Opportunistic Routing

A detailed survey and concepts of opportunistic routing were discussed in Chapter 2. In this section, a brief overview of OR protocols is presented especially to describe the two protocols EEOR [82] and OOF [73].

In opportunistic routing neighbourhood nodes are arranged in forwarder list with respect to certain priority. Low priority nodes discard the overheard packet, if they hear the transmission of packet from a higher priority node. ExOR [15], geographic random forwarding (GeRaF) [122], and efficient QoS-aware geographic opportunistic routing (EQGOR) [26] use neighbourhood nodes to relay packets. However, these protocols do not have any optimal mechanism for creating an appropriate forwarding list to reduce energy cost. Moreover, ExOR is designed for static mesh network and is not suitable for energy constrained mobile networks. Opportunistic relative distance enabled unicast routing (ODEUR) [77], is designed for MWSNs with intermittent connectivity and multiple alternative sinks, especially observed in wildlife or habitat monitoring applications. The protocol neither minimizes energy consumption nor optimizes the data forwarding. Moreover, the results presented lack benchmarking.

Mao et. al. [82] have proposed energy efficient opportunistic routing (EEOR) protocol for MWSNs with an objective to optimize the selecting and prioritizing the

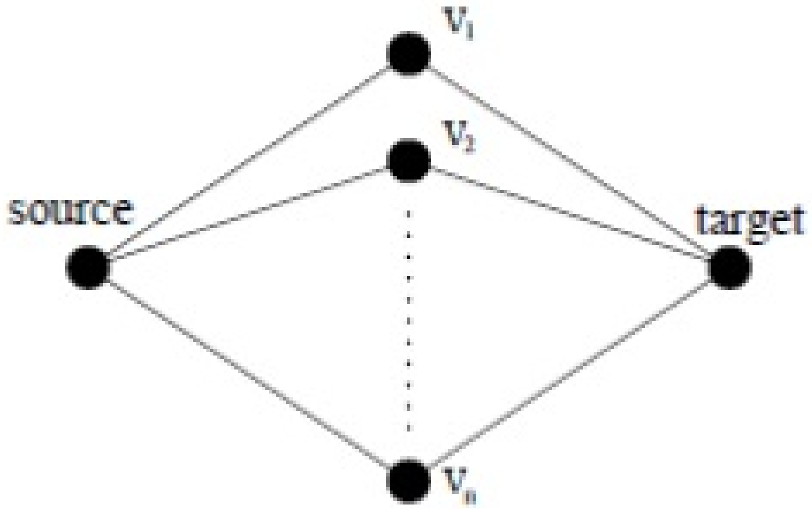

FIGURE 4.1: EEOR packet forwarding

forwarder list. The forwarder list of a node is calculated as subset of neighbourhood nodes. The expected cost of a node is computed based on the cost incurred by neighbourhood node for sending the packet to the destination and cost of transmitting the packet to neighbourhood nodes. The forwarding policy of EEOR is shown in Figure 4.1. Source node has $v_1, v_2, \cdots, v_n$ nodes in the forwarder list to which, it transmits the packet. It is expected that only one node in the forwarder list should relay the packet to target node. For this the nodes in the forwarder list should have coordination among themselves. However, EEOR does not implement such coordination among the forwarder list nodes. As a result, the nodes in the forwarder list relay the packet independent of each other, increasing the packet duplicates. The packet duplicates unnecessarily consume the network bandwidth and energy. Lack of coordination increases avoidable network traffic, overheads as well as energy consumption. This will scale much faster, if in case, the network has dense deployment of the nodes as the forwarder list will have large number of nodes as its members.

Cong Liu et. al. [73] have presented optimal opportunistic forwarding (OOF) and its simplification, designated as OOF-, for intermittently connected networks, which maximize delivery rate and minimize delay. OOF maximizes the expected delivery probability and OOF- minimizes the expected delay. Both the algorithms focus on minimizing the number of copies of message in multi-copy network environments. The design of OOF family protocols is based on hop count forwarding. A threshold based optimal stopping rule is used to perform message forwarding decisions. OOF and OOF- assume a pre-determined node inter-meeting schedule in intermittently connected networks. However, in mobile applications it is difficult for mobile nodes to follow pre-determined inter-meeting times and so this may lead to sub-optimal performance. Also for maintaining an inter-meeting schedule, nodes require large computational capacity, time, as well as storage. It would be interesting to investigate OOF for computational complexity and its use in time critical applications.

It can be observed that the existing opportunistic protocols proposed for MWSNs have limitations such as higher energy consumption, large overhead due to duplicate packet forwarding, lack of robustness and unsuitable for networks with intermittent connectivity. Keeping in view these issues, the following section presents the design of connectivity based energy efficient opportunistic robust (CBEEOR) routing protocol, which minimizes energy cost, reduces duplicate packet transmissions and provides robustness against node/ link failures.

4.3 Design of CBEEOR

CBEEOR routing protocol is designed for MWSNs and is an opportunistic routing protocol. The protocol is designed for MWSNs comprising of homogeneous sensor nodes. It is presumed that the data generation in MWSN is much slower compared to the data transmission rate. For eg. in a pollution monitoring application, various parameters monitored do not change their value for duration upto 30 minutes whereas data delivery is completed within maximum period of $1-2$ seconds. The MWSN is modelled as graph $G = (V, E)$, where V is the set of vertices representing the mobile nodes and E is set of edges representing the communication links between the nodes which are separated by distance not greater than transmission range of the node. Each node u maintains the information of nodes within its transmission range called as neighbourhood nodes denoted by $N(u)$. Energies $e_t(u, v)$ and $e_r(u, v)$ represent energy consumed for sending and receiving a packet respectively. The error probability of link is denoted by p_{uv}. The design of CBEEOR involves computation of expected cost and relay node selection, for minimizing energy, avoiding duplicate transmissions and reducing overheads. The expected cost is calculated based on the two criteria given below:

- Algebraic connectivity of the graph [39], [55].
- Energy consumption for packet transmission, relaying and delivery probability of the link.

4.3.1 Computation of Expected Cost

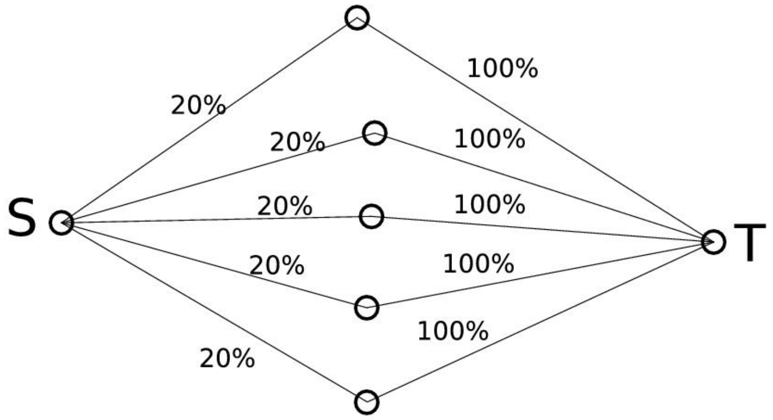

FIGURE 4.2: Example for CBEEOR versus traditional routing

The expected cost of forwarding the data to sink is estimated as a combination of energy consumed for data forwarding and algebraic connectivity link cost. The energy consumed by a node u for data forwarding is estimated using a forwarder list similar to EEOR [82]. The forwarder list of node u is subset of neighbourhood nodes $N(u)$ i.e. $Fwd(u) \subseteq N(u)$. The nodes are added in $Fwd(u)$ based on the expected cost of forwarding the packet to neighbourhood nodes. The forwarder list $Fwd(u)$ is the prefix set of $N(u)$. Figure 4.2 illustrates how relay-based opportunistic routing is used in CBEEOR. A source node S sends the data to target node T using the intermediate nodes. Each edge is a wireless link with delivery probability as links weight. CBEEOR, as explained in Chapter 2, selects all the neighbour nodes as potential relay nodes i.e. each node is in $Fwd(u)$ and thus could achieve delivery probability of $(1 - (1 - 0.2)^5) = 67\%$. The traditional routing protocol selects only one link amongst the available links and thus achieves only 20% delivery probability. $Fwd(u)$ is sorted in increasing order of the expected cost of forwarding called as prioritized forwarder list denoted by $Fwd^*(u)$ and given as $Fwd^*(u) = \{v_1, v_2, \ldots, v_{|Fwd(u)|}\}$ where $i < j \longrightarrow C_{v_i} \leq C_{v_j}$, where C_v is the expected cost. A node $v \in N(u)$ is added to $Fwd^*(u)$ if the expected cost of node v does not exceed the expected cost $C_U^h(Fwd^*)$ of node u. The cost incurred by node u for sending a packet and its successful reception by atleast one node v in the forwarder list $Fwd^*(u)$ depends on energy consumed for transmission and delivery probability of wireless links represented by Equation 4.1.

$$\begin{aligned} C_u^h(Fwd^*) &= \frac{w}{\rho} \\ &= \frac{e_t(u,v) + e_r(u,v)}{1 - \Pi_{i=1}^{|Fwd^*|} p_{uv_i}} \end{aligned} \tag{4.1}$$

The prioritized forwarder list of node u is denoted by $Fwd^*(u) = \{v_1, v_2, \ldots, v_{|Fwd(u)|}\}$. The probability that node v_1 forwards the packet is $(1 - p_{uv_1})$ and its expected cost is C_{v_1}. Node v_2 will forward the packet with probability $p_{uv_1} \cdot (1 - p_{uv_2})$ and its cost is C_{v_2}. Theoretically, it is expected that only one node in $Fwd^*(u)$ should forward the data packet to avoid duplicate transmissions and Equation 4.2 gives the expected cost for the same. Coordination and cooperation among the nodes in the forwarder list is required so that only one node forwards the data. In absence of such coordination, multiple nodes in the forwarder list will relay the packet independent of each other. Implementing coordination in the routing protocol will increase the overheads as well as energy consumption. So in CBEEOR, a back-off time mechanism is incorporated to minimize the duplicate transmissions by nodes in the forwarder list, which is not used in EEOR [82]. The Equation 4.3 gives the cost when multiple nodes in the forwarder list relay the same packet towards the sink.

$$\beta = (1 - p_{uv_1}) \cdot C_{v_1} + \Sigma_{i=2}^{|Fwd^*|} (\Pi_{j=1}^{i-1} p_{uv_j}) \cdot (1 - p_{uv_i}) \cdot C_{v_i} \tag{4.2}$$

$$\beta_m = \Sigma_{i=1}^{|Fwd^*|} (\Pi_{j=1, v_j \in N(v_i)}^{i-1} p_{uv_j}) \cdot (1 - p_{uv_i}) \cdot C_{v_i} \tag{4.3}$$

The value of β_m given in Equation 4.3 helps to determine the expected cost incurred for forwarding the data towards the sink, when multiple nodes in the forwarder list transmit the data packet. Considering the error probability of the wireless links the cost is calculated as given by Equation 4.4.

$$\begin{aligned} C_u^f(Fwd^*) &= \frac{\beta_m}{\rho} \\ &= \frac{\Sigma_{i=1}^{|Fwd^*|}(\Pi_{j=1,v_j \in N(v_i)}^{i-1} p_{uv_j}) \cdot (1-p_{uv_i}) \cdot C_{v_i}}{1-\Pi_{i=1}^{|Fwd^*|} p_{uv_i}} \end{aligned} \tag{4.4}$$

In CBEEOR, while computing the expected cost of forwarding, the network connectivity is given importance as the node which keeps the network highly connected should preferably be selected to relay the data packets. Network connectivity plays an important role as the network will remain operational as long as it is connected. The connectivity attribute of any node u is quantified as algebraic connectivity $a(G_{-u})$ of the graph excluding the node u and edges incident from u [39]. The algebraic connectivity of the graph is second smallest eigenvalue of the Laplacian matrix $L(G)$ calculated as $L(G) = D(G) - A(G)$ where $D(G)$ is the degree matrix and $A(G)$ is the adjacency matrix. For the two graphs $G_1 = (V, E_1)$ and $G_2 = (V, E_2)$ such that $|E_1| \leq |E_2|$, $a(G_1) \leq a(G_2)$ [39], which determines that the graph G_2 is better connected then G_1. Thus, larger the value of $a(G)$, the graph G is strongly connected. Example 4.1 illustrates how to determine $a(G)$, Example 4.2 illustrates application of $a(G)$ in design of CBEEOR and Example 4.3 shows how algebraic connectivity varies for the graph with same number of vertices but different number of edges. .

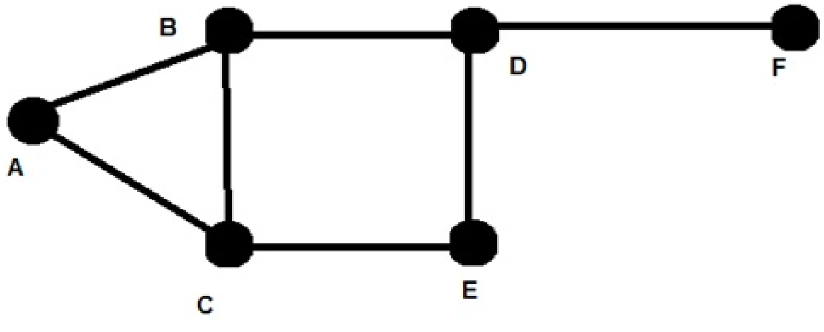

FIGURE 4.3: Example to calculate algebraic connectivity

Example 4.1. *The algebraic connectivity [39] calculation is illustrated using Figure 4.3. Initially, the adjacency matrix* $A(G)$ *for the graph* G *is constructed.*

$$A(G) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$D(G) = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$L(G) = D(G) - A(G) = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 \\ -1 & 3 & -1 & -1 & 0 & 0 \\ -1 & -1 & 3 & 0 & -1 & 0 \\ 0 & -1 & 0 & 3 & -1 & -1 \\ 0 & 0 & -1 & -1 & 2 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix}$$

Eigenvalues λ *of the above Laplacian matrix of the graph in Figure 4.3 are observed to be* 0, 0.7216, 1.6826, 3, 3.7046, 4.8912*. The second smallest eigenvalue* 0.7216 *is called as algebraic connectivity* $a(G)$ *of graph.*

Example 4.2 explains how algebraic connectivity is applied in design of CBEEOR. The algebraic connectivity $a(G_{-u})$ is calculated for every vertex u of the graph in Figure 4.3 by removing that vertex and its incident edges. The process is illustrated for node D and A of Figure 4.3; Figure 4.4 and Figure 4.5 show the modified graph obtained after removing the vertex D and A respectively. Figure 4.4 shows that the graph is partitioned after removing vertex D.

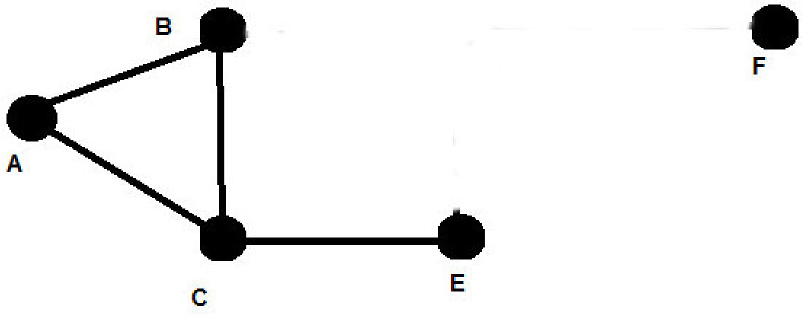

FIGURE 4.4: Algebraic connectivity for network in Example 4.1 after deleting vertex D

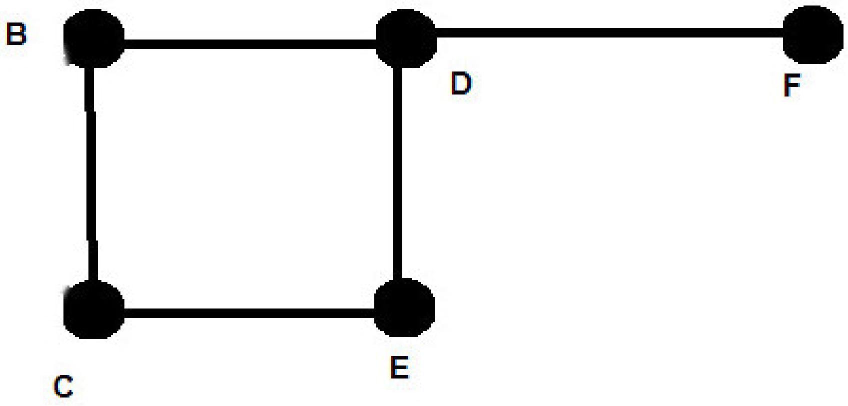

FIGURE 4.5: Algebraic connectivity for network in Example 4.1 after deleting vertex A

Example 4.2. *The adjacency graph* $A(G_{-D})$ *is*

$$A(G_{-D}) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The diagonal matrix $D(G_{-D})$ *is*

$$D(G_{-D}) = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Laplacian matrix is

$$L(G_{-D}) = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ -1 & -1 & 3 & -1 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Eigenvalues λ *of the above Laplacian matrix of the graph in Figure 4.4 are observed to be* 0, 0, 1, 3, 4. $a(G_{-D})$ *is* 0 *stating that graph is disconnected. If the vertex* A *is removed from Figure 4.3 to obtain modified graph Figure 4.5 and Laplacian matrix* $L(G_{-A})$ *is*

$$L(G_{-A}) = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 \\ -1 & 2 & 0 & -1 & 0 \\ -1 & 0 & 3 & -1 & -1 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Eigenvalues for Figure 4.5 are 0, 0.8299, 2, 2.688, 4.481. $a(G_{-A})$ *is* 0.8299

Example 4.3. *This example illustrates how algebraic connectivity* $a(G)$ *varies for a graph with same number of vertices and different number of edges shown in Figure 4.6 and Figure 4.7. For the Figure 4.6 the matrices* $A(G)$, $D(G)$ *and* $L(G)$ *can be written as follows*

FIGURE 4.6: Example to calculate algebraic connectivity

$$A(G) = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

$$D(G) = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix}$$

$$L(G) = D(G) - A(G) = \begin{bmatrix} 2 & -1 & 0 & -1 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ -1 & 0 & -1 & 2 \end{bmatrix}$$

The eigenvalues λ *of the above Laplacian matrix are* 0, 2, 2 *and* 4. *Algebraic connectivity* $a(G)$ *i.e. the second smallest eigenvalue is* 2. *Now lets augment the network with two diagonal edges as shown in Figure 4.7. The three matrices for this network graph can be written as*

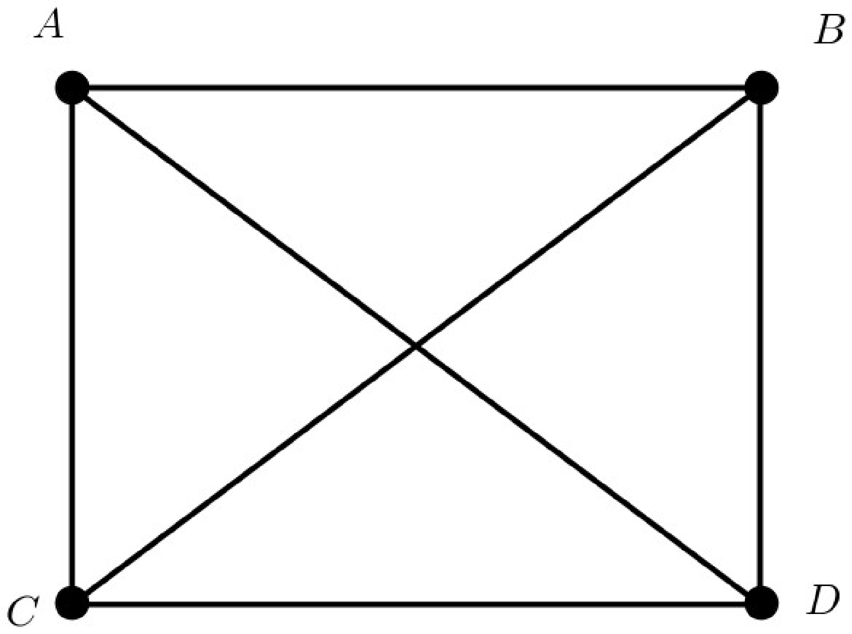

Figure 4.7: Example to calculate algebraic connectivity

$$A(G) = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

$$D(G) = \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 3 \end{bmatrix}$$

$$L(G) = D(G) - A(G) = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}$$

The eigenvalues λ *of the above Laplacian matrix are* 0, 4, 4 *and* 4. *Algebraic connectivity* $a(G)$ *i.e. the second smallest eigenvalue is* 4. *This clearly illustrates the* *hypothesis proposed by Feidler [39], that if* $a(G_2) > a(G_1)$ *then connectivity in network graph* G_2 *is higher than connectivity in network graph* G_1.

In CBEEOR, the $a(G)$ is calculated for each node in the forwarder list. The connectivity based cost for node u denoted by $C_u^{cb}(Fwd^*)$ is calculated as energy required for transmitting and receiving the packet relative to the algebraic connectivity of transmitter and receiver respectively, shown in Equation 4.5. As can be readily seen that if the algebraic connectivity is higher the cost for forwarding is reduced appropriately.

$$C_u^{cb}(Fwd^*) = \frac{e_t(u,v)}{a(G_{-u})} + \frac{e_r(u,v)}{a(G_{-v})},\ a(G_.) > 0 \tag{4.5}$$

$$C_u(Fwd^*) = C_u^h(Fwd^*) + C_u^f(Fwd^*) + C_u^{cb}(Fwd^*) \tag{4.6}$$

Thus, in CBEEOR routing protocol, the expected cost of a sender to broadcast a packet if the current chosen forwarder list is Fwd^*, is calculated using Equation 4.6. The expected cost of forwarding $C_u(Fwd^*)$ is combination of three cost components as listed below:

1. Cost of data packet transmission to nodes in the forwarder list denoted by $C_u^h(Fwd^*)$ determined using Equation 4.1.
2. Cost of relaying the packet by one or more nodes in the forwarder list to target node denoted by $C_u^f(Fwd^*)$ determined using Equation 4.4 and,
3. Cost based on network connectivity denoted by $C_u^{cb}(Fwd^*)$ determined using Equation 4.5.

The forwarder list Fwd^* is thus prioritized based on the cost $C_u(Fwd^*)$ given in Equation 4.6. Having decided the cost of forwarding as per Equation 4.6 to avoid duplicate packet transmissions, the coordination among the forwarder nodes becomes important, which is described in the following subsection.

4.3.2 Coordination among Forwarder Nodes

The Equation 4.6 computes the expected cost of forwarding the packet through the nodes in the forwarder list $Fwd^*(u) = \{v_1, v_2, \ldots, v_{|Fwd(u)|}\}$. The node with smallest expected cost is selected as the forwarder node. In case the selected forwarder node is not available due to mobility or failure, the transmitted packet should be forwarded by other nodes in the forwarder list. These nodes act as backup node and become opportunist to relay the packets. Two classes of backup nodes are defined namely equivalent nodes and remedy nodes. The equivalent nodes denoted by N_e are the nodes that are neighbour nodes of both the sender and receiver of the packet. The remedy nodes denoted by N_r are the nodes that are neighbours of sender and not of receiver. Whether a node is equivalent or remedy node is decided by the node itself as each node has the neighbourhood information and the sender as well as receiver can be known from the data packet. For nodes u and v, $N_e(u) = N(u) \bigcap N(v)$ and $N_r = N(u) - N(v)$. For example, as seen from the Figure 4.8, let node u be the sender and node v be the receiver. The packet forwarded by node u to v is also overheard due to broadcast nature of wireless transmission by nodes $1, 2, 3, 4, 5, 6$. Nodes $1, 2, 3$ are common neighbours of node u and node v and therefore are equivalent nodes, whereas nodes $4, 5, 6$ are neighbours to u only and so are remedy nodes.

CBEEOR uses a back-off time mechanism to decide either any of the equivalent nodes or remedy nodes should take-up data packet relaying if the intended node fails or is not available due to node mobility. The motivation for using the back-off time mechanism for selecting the relay node is the work proposed by Huang et. al. [49] in design of RRP. The MAC protocol is used differently in CBEEOR compared to RRP. The protocol RRP assumes that the path between source and target called intended path is established and nodes on the path forward the data hop-by-hop. In case any node on the path has moved, then the neighbour nodes forward the packet to the moved node or its next relay node on the intended path. In CBEEOR, the neighbourhood nodes use their own forwarder list to determine who should be the next relay node if the receiver of the packet moves or fails. To minimize the multiple transmissions of the same packet by nodes in the forwarder list the back-off time mechanism is used.

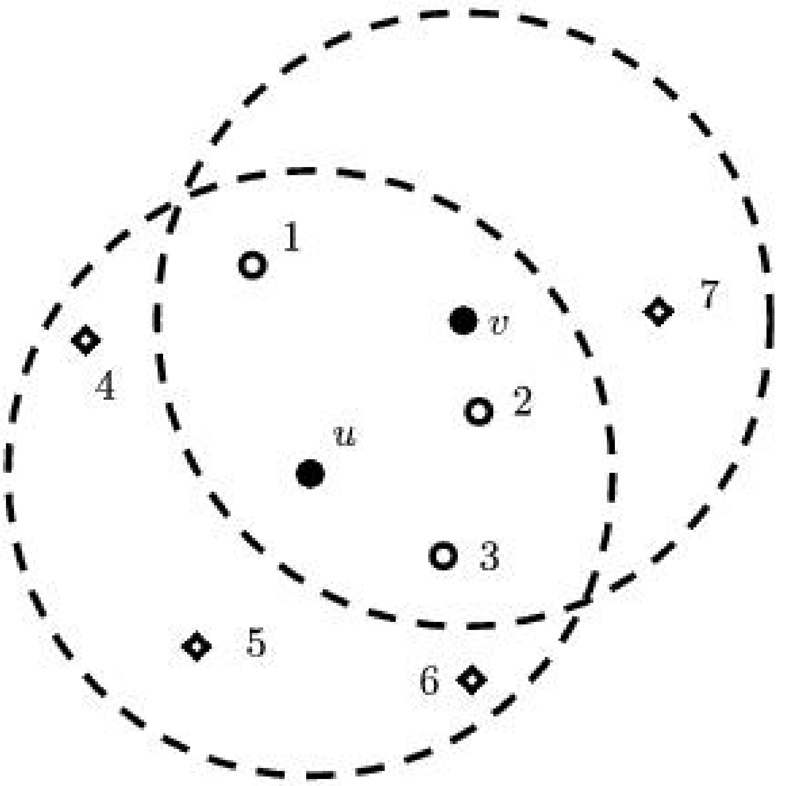

FIGURE 4.8: Remedy nodes and equivalent nodes for node u

The Figure 4.9 and Figure 4.10 show the working and Equation 4.7, Equation 4.9 determine back-off time mechanism for equivalent and remedy nodes respectively, similar to the approach used in design of RRP [49]. Both the equivalent and remedy nodes start counting the back-off time as soon as the short interframe space (SIFS) expires. An equivalent node $v \in N_e$ with a shortest back-off time $D_{be,v}$ calculated using Equation 4.7, is the first to reply with an acknowledgement (ACK). D_e is the back-off window for equivalent nodes, K_v determined using Equation 4.8, is the mixed metric of normalized link delay T_v and the error probability p_{uv} of the link between node u and v. M_v is the relative mobility speed, which is in the range $[0.01, 1]$. The other nodes in N_e, as well as N_r, stop participating once they sense the ACK, hence the election for the relay node ends. The back-off time for the equivalent nodes is no greater than $SIFS + D_e$. If there is no ACK sensed before D_e ends, then it indicates that no equivalent node is available.

$$D_{be,v} = SIFS + D_e \cdot M_v \cdot K_v \;\; for\, node\, v \in N_e \tag{4.7}$$

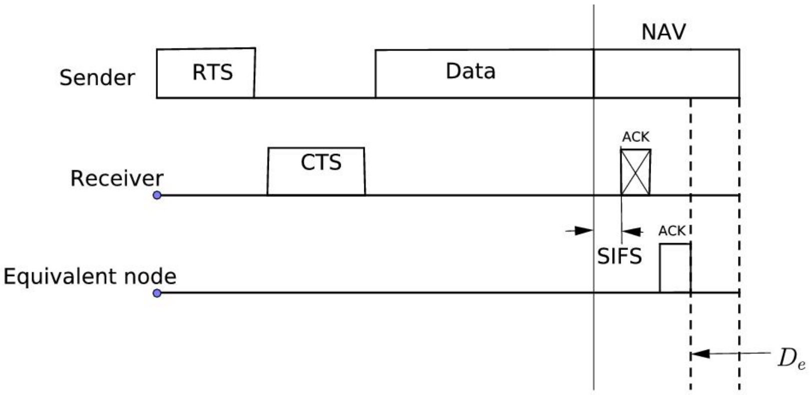

FIGURE 4.9: Back-off time mechanism for equivalent nodes

where

$$K_v = \frac{T_v}{1 - p_{uv}} \tag{4.8}$$

Remedy nodes will have lesser priority to relay than equivalent nodes and have their backoff time $D_{br,r}$ determined using Equation 4.9. D_r is the back-off window for remedy nodes. The maximum back-off time for remedy nodes is $SIFS + D_e + D_r$. K_r, M_r play a role similar to K_v and M_v as in Equation 4.7. The back-off time for equivalent and remedy nodes cannot be estimated precisely, but maximum back-off time can be determined. The network allocation vector (NAV) in IEEE 802:11 for all the nodes is altered as given in Equation 4.10. D_{max} denotes the maximum back-off time that should be large enough to reduce the probability of ACK collision among relaying nodes.

$$D_{br,r} = SIFS + D_e + D_r \cdot M_r \cdot K_r \;\; for\, node\, r \in N_r \tag{4.9}$$

$$NAV = NAV_{802.11} + D_e + D_r = NAV_{802.11} + D_{max} \tag{4.10}$$

Thus, the CBEEOR with two separate delay mechanisms, one for equivalent nodes and the other for remedy nodes, provides adequate backup for robust routing in case of node mobility or failures, unreliable as well as intermittent links. In CBEEOR design, WBA [109] and the delay mechanism for node coordination help to have alternate paths through available neighbourhood nodes for effective and ensured data forwarding, which avoids multiple retransmissions, minimizes overheads and further

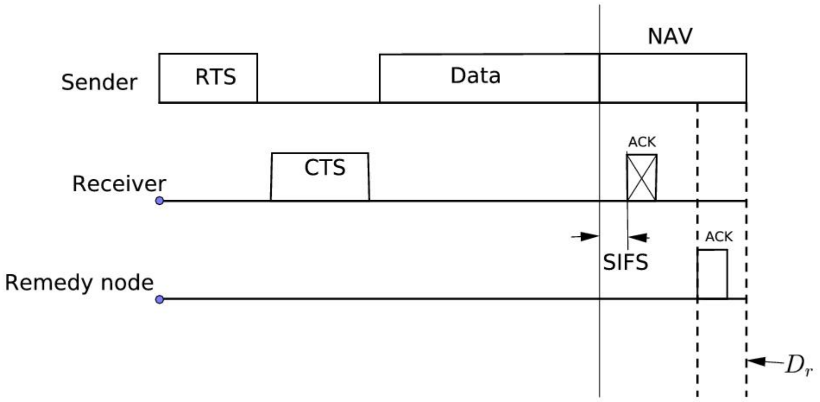

FIGURE 4.10: Back-off time mechanism for remedy nodes

reduces the overall energy consumption. CBEEOR protocol is thus expected to seamlessly adapt to frequent topology changes due to node mobility, making it suitable for networks with intermittent connectivity. The use of algebraic connectivity in estimating the expected opportunistic cost of forwarding preferably selects the routes that keep the network highly connected.

4.4 Simulation and Results

The simulations are performed in a network of size 750 meter x 750 meter with all the nodes mobile. The simulation time is 50 seconds. For the experimental purpose the value of a(G) is considered as 10^{-6} to avoid division error, if $a(G) = 0$. All the results represent average of performance parameters for 20 simulation runs for averaging out the randomness in placement of nodes. The simulations are performed using network simulator 2 (NS2). The simulation settings and parameters are summarized in Table 4.1. CBEEOR, EEOR [82] and OOF [73] are compared for performance parameters namely packet delivery, packet drops, residual energy, routing overheads and end-to-end delay. Two scenarios are considered for simulation to evaluate and compare the performance of all the three protocols for network scalability and node mobility respectively.

Sr. No.	Parameter	Value
1	Number of Nodes	100, 200, 300 and 400
2	Area Size	$750 \times 750m^2$
3	Simulation Time	$50seconds$
4	Traffic Source	CBR
5	Packet Size	512 bits
6	Rate	150 kbps
7	Mobile node speed	5, 10, 15,20 and $25m/s$
8	Initial Energy	12.3 $Joules$
9	Transmission Power	0.660 W
10	Receiving Power	0.395 W
11	Transmission Range	$40m$

Table 4.1: Simulation Parameters for CBEEOR

4.4.1 Scenario I: Network Scalability

In this scenario, the performance of CBEEOR routing protocol is examined by scaling the network for number of nodes. To examine this, the number of nodes is varied from 100 to 400. The mobility speed of all the nodes is kept constant at $5m/s$. The Figure 4.11, Figure 4.12, Figure 4.13, Figure 4.14 and Figure 4.15 show the performance of the protocols in view of the network scalability. The packet delivery function, defined as per Equation 3.3, for CBEEOR is better by approximately $45 - 50\%$ compared to EEOR ($8 - 10\%$ better compared to OOF) as seen from the Figure 4.11. This is due to the ability of CBEEOR to adapt to changing topology of the dynamic network. The Figure 4.12 shows that the packet drops, defined as per Equation 3.9 for CBEEOR are approximately 40% less compared to EEOR ($22 - 25\%$ less compared to OOF). The routing overheads, defined as per Equation 3.8 are shown in Figure 4.13. CBEEOR reduces the overheads by $12 - 15\%$

compared to EEOR ($4-8\%$ less compared to OOF). The backup nodes make the packet relay resilient to effects of path breakages, which reduce frequent computation of paths. In EEOR, the mobile nodes make the forwarder list invalid and the protocol needs repeated computation. The energy consumption is determined using Equation 3.7. It is observed from the Figure 4.14, that the energy consumption in CBEEOR is $25-30\%$ less compared to EEOR ($6-10\%$ less compared to OOF). End-to-end delay as per Equation 3.4 and shown in Figure 4.15 is also approximately 2.5 seconds less compared to EEOR (0.2 to 1.0 seconds less compared to OOF). Thus CBEEOR shows significant improvement in performance for all the parameters compared to EEOR [82] and some marginal improvements when compared with OOF [73] due to provision of backup nodes. This ensures that the data packets are always delivered and the need for retransmission is minimized.

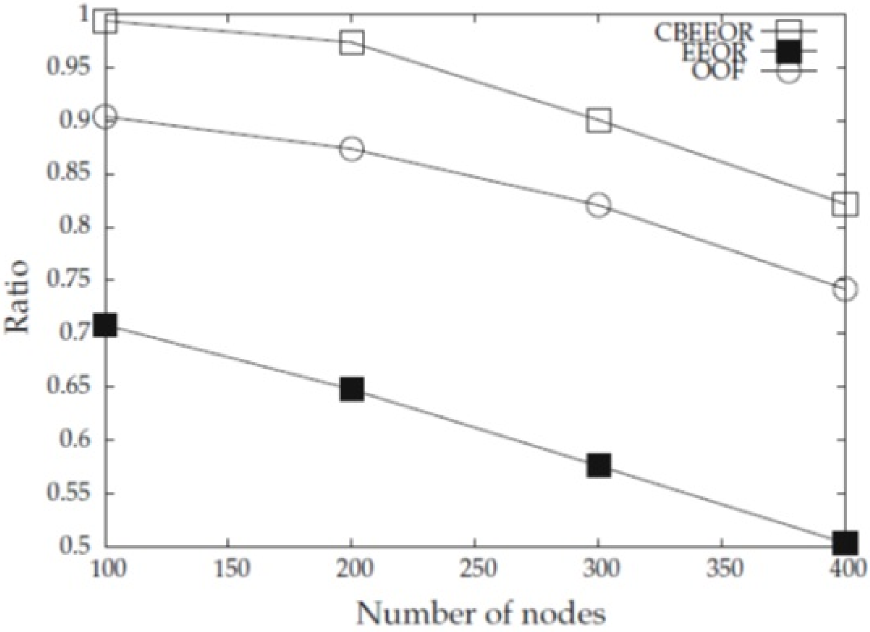

FIGURE 4.11: Packet delivery function for varying number of nodes

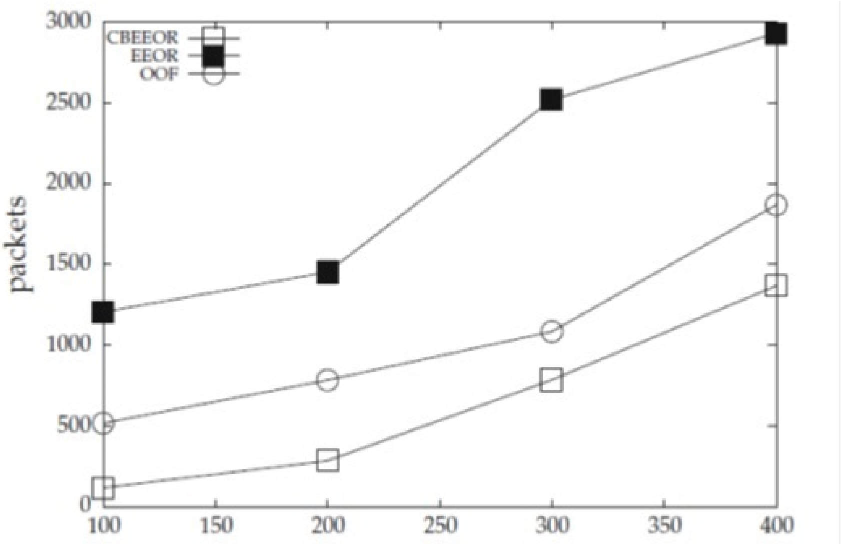

Figure 4.12: Packet drops for varying number of nodes

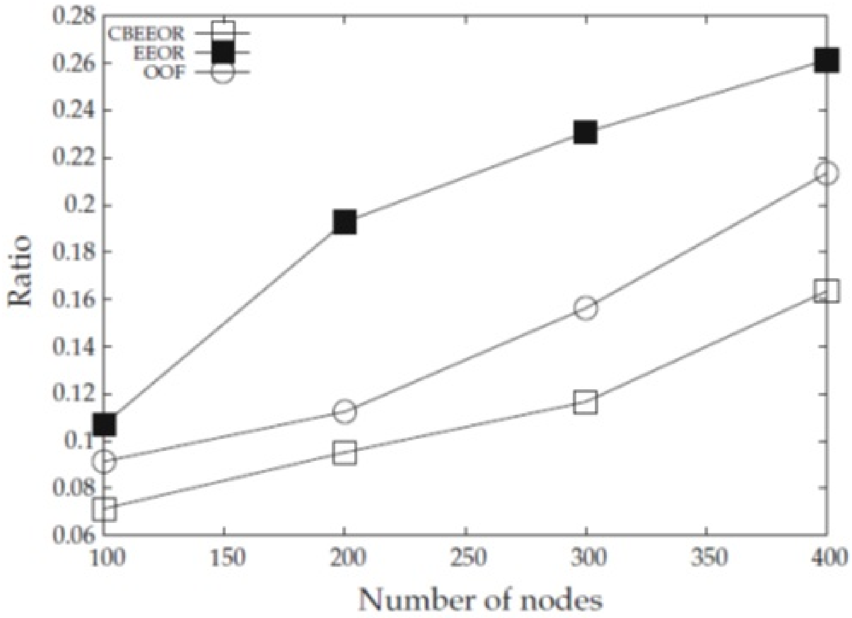

Figure 4.13: Routing overheads for varying number of nodes of nodes

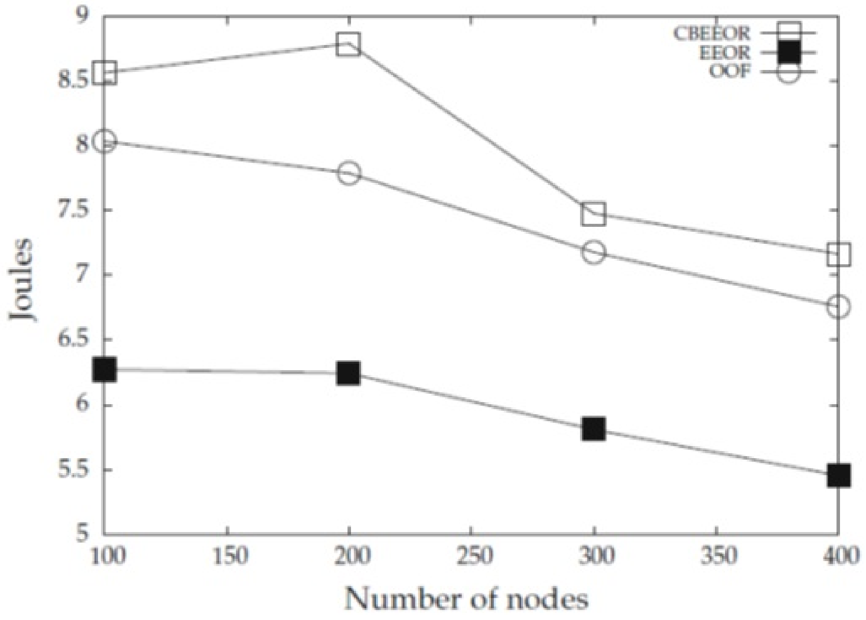

FIGURE 4.14: Residual energy for varying number of nodes

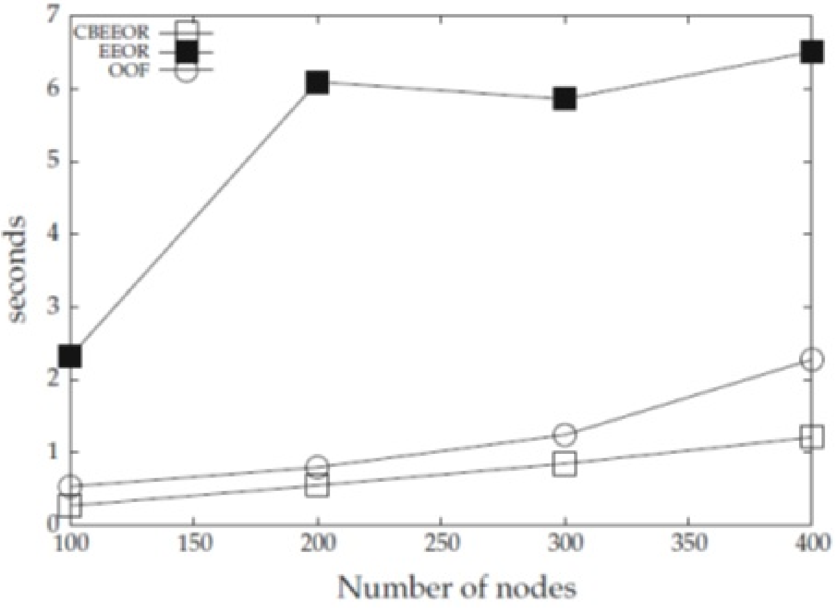

FIGURE 4.15: End-to-end delay for varying number of nodes

4.4.2 Scenario II: Node Mobility

To evaluate the performance of CBEEOR for mobile nodes, in the second experiment, the speed of the nodes is varied from $5m/s$ to $25m/s$. The numbers of nodes for the simulation are kept constant equal to 100. Figure 4.16, Figure 4.17,Figure 4.18, Figure 4.19 and Figure 4.20 show the comparative performance for three protocols namely OOF [73], EEOR [82] and CBEEOR. Figure 4.16 shows that CBEEOR provides approximately 30% higher packet delivery function compared to EEOR ($8-10\%$ higher compared to OOF). It can be readily seen from Figure 4.17, CBEEOR reduces packet drops by $20-25\%$ compared to EEOR (8% compared to OOF). CBEEOR reduces routing overheads by $25-30\%$ compared to EEOR ($10-12\%$ compared to OOF) as shown in Figure 4.18. It can be observed from the Figure 4.19, CBEEOR requires 30% less energy compared to EEOR ($10-12\%$ less compared to OOF). CBEEOR shows an improvement of 4 to 6 seconds for end-to-end delay compared to EEOR (approximately 1.0 to 1.2 seconds improvement over OOF), as seen in Figure 4.20. As the mobility speed increases, the performance degrades for all the three protocols, due to more frequent topology changes and increased unavailability of forwarder nodes. However, because of the backup mechanism built through the provision of equivalent and remedy nodes, CBEEOR gives much better performance as compared to other two protocols due to efficient and effective routing of packets to sink using alternative paths. OOF [73] which is designed for intermittently connected networks performs much better compared to EEOR [82] for MWSNs. However, CBEEOR performs marginally better than OOF for both the scenarios, namely network scalability and node mobility, thus justifying the suitability of CBEEOR for intermittent networks.

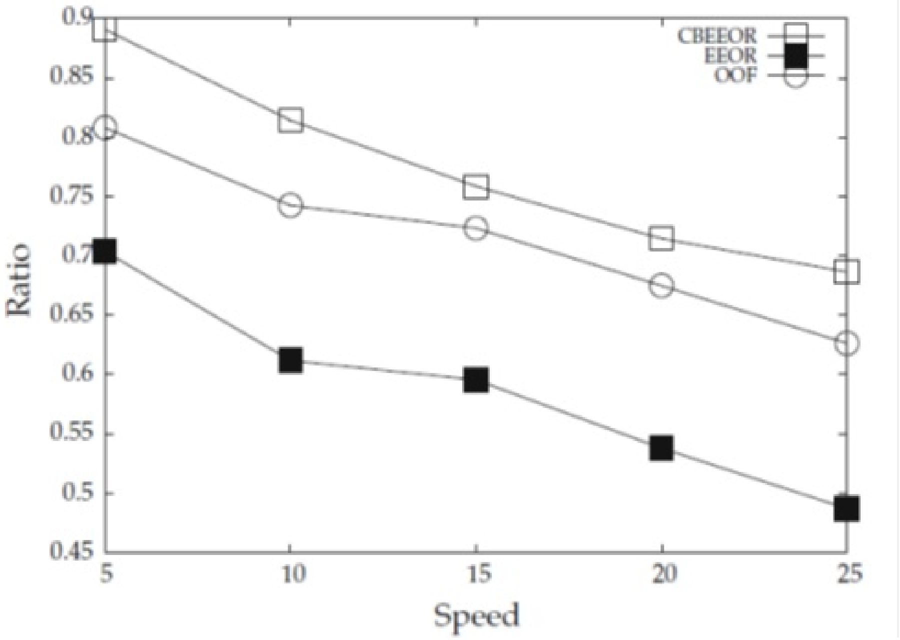

Figure 4.16: Packet delivery function for varying node movement speed

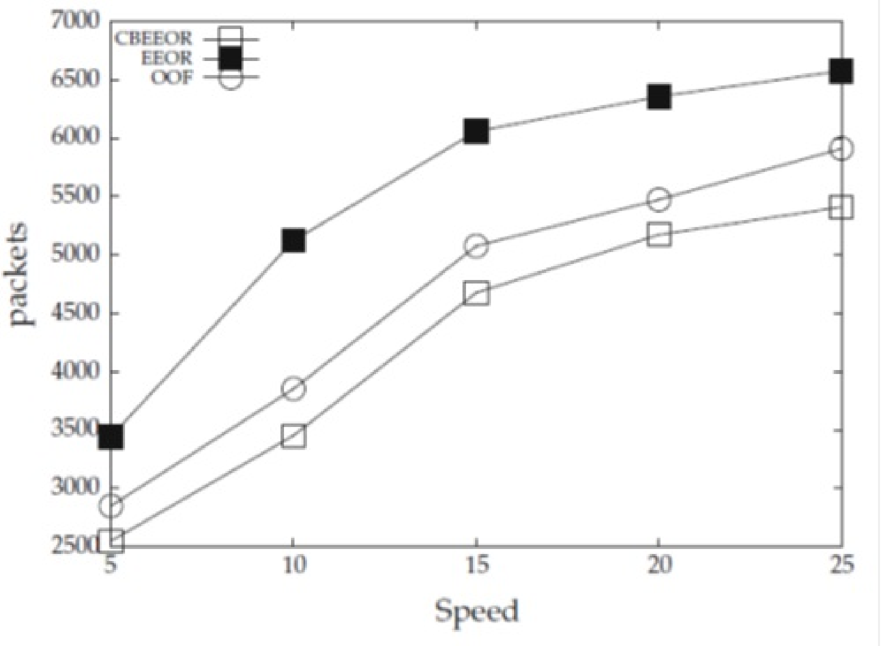

Figure 4.17: Packet drops for varying node movement speed

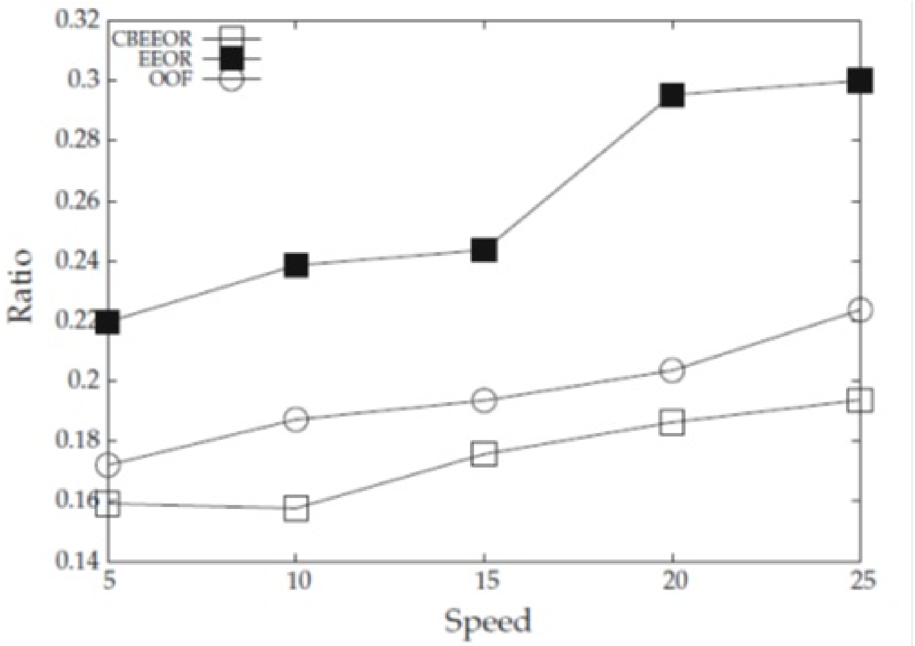

FIGURE 4.18: Routing overheads for varying node movement speed

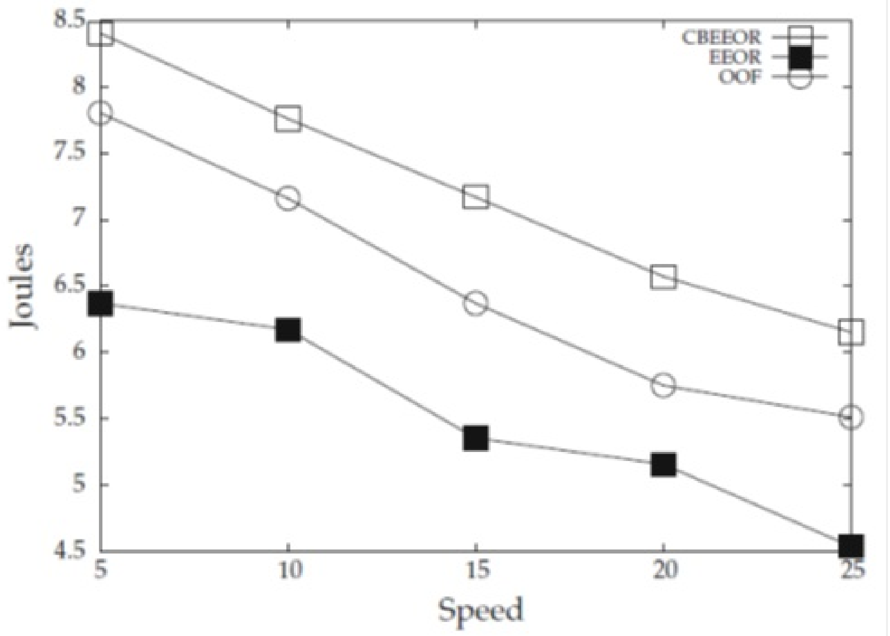

FIGURE 4.19: Residual energy for varying node movement speed

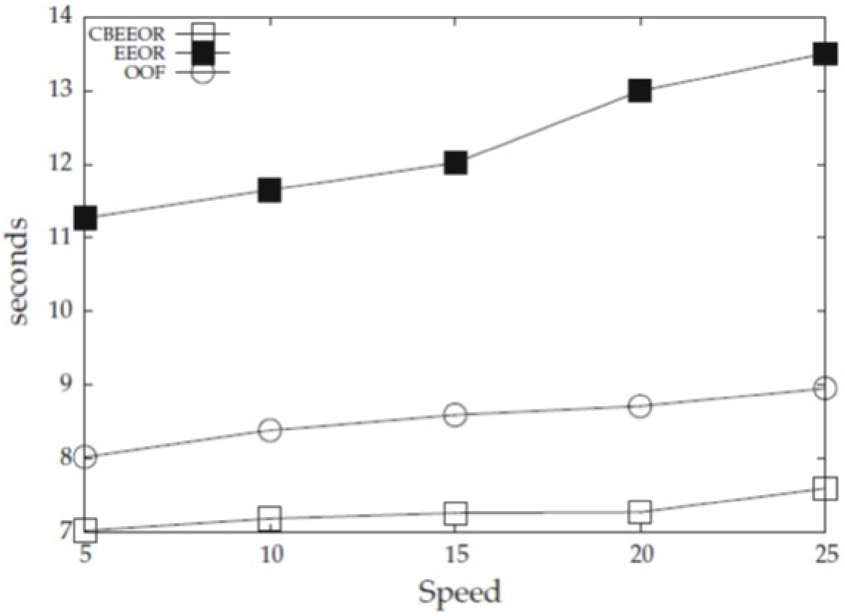

FIGURE 4.20: End-to-end delay for varying node movement speed

4.5 Conclusion

Thus, in this chapter design of CBEEOR routing protocol and its performance evaluation in comparison with EEOR and OOF are presented. The algebraic connectivity, prioritized forwarder list and backoff time for coordination among the backup nodes are implemented for effective data forwarding. The back-off time factor is implemented to determine the relay node in case of moving away or failure of forwarding node. The back-off time mechanisms also avoids packet collisions among the equivalent and remedy nodes, as well as avoids retransmissions from the sender and hence reduces the overheads in the network. CBEEOR exhibits better performance of over 30% compared to EEOR and 8% compared to OOF for packet delivery. Improvement of 25% compared to EEOR and 6% compared to OOF is observed for energy consumption CBEEOR also shows improvements approximately in the range of $20 - 25\%$ compared to EEOR and $10 - 12\%$ compared to OOF for other parameters. Comparison of CBEEOR performance with OOF and improvements exhibited makes CBEEOR suitable even for intermittently connected networks.

In the design of CBEEOR, it is assumed that data generation rate is much lower compared to data delivery rate. Therefore, the probability of simultaneous data transmission from different nodes is very small. However, there may be some applications or networks with very large number of nodes, wherein multiple nodes may have to transmit almost at the same time. Therefore, the performance of CBEEOR may need to be investigated in such applications and/ or network scenarios.

CBEEOR can be improved further to have better packet delivery in node mobile environments. In the next chapter, another opportunistic routing protocol named as cross-layer connectivity-based opportunistic forwarding (CCOF), which is an improvement over CBEEOR presented in this chapter, particularly for packet delivery function especially for dynamic network environment, is discussed.

[1]

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[1] This work has been published and details are: Mandar Karyakarte, Anil S. Tavildar and Rajesh Khanna “Connectivity Based Energy Efficient Opportunistic Robust Routing for Mobile Wireless Sensor Networks”, Springer Wireless Personal Communications, Vol 84, issue 1, DOI 10.1007/s11277-015-2658-x SCIE indexed, Impact factor: 0.98.

Chapter 5

Design and Simulation of Connectivity-based Cross-layer Opportunistic Forwarding

In this chapter, the design of Connectivity-based Cross-layer Opportunistic Forwarding (CCOF) protocol and its performance is evaluated in comparison with energy efficient opportunistic routing (EEOR) [82], ad-hoc on-demand multipath distance vector (AOMDV) [83] and destination sequenced distance vector (DSDV) [92] routing protocols.

5.1 Introduction

The need of a routing protocol for MWSNs that suits to mobility and also minimizes energy consumption has been illustrated through the literature review presented in chapter 2, as well in Section 4.1 earlier. In this context, we have proposed in the previous chapter a new routing protocol CBEEOR, which provides considerable performance improvements with respect to EEOR. However it is possible to make some further improvements in CBEEOR with respect to the following

1. Try to avoid two delay mechanisms and reduce to it to single level, thus improving the performance for time critical applications.

2. Use of mobility parameter in working out the priority of forwarding and dynamically adjusting the forwarding list, while prioritizing the relay nodes.
3. Merge the node connectivity aspect in transmitting and forwarding cost computations for generation of priority list

In CCOF, the expected cost of forwarding is computed as combination of node connectivity and energy consumption. CCOF also reduces the packet retransmissions using a forwarding agreement. Node connectivity in CCOF determines effect of a particular node on MWSN partitioning, if it fails. The Section 5.2 presents a description related to the mathematical approach for expected cost calculation followed by design of forwarding agreement mechanism which enables coordination among the forwarder nodes to ensure that only a single copy of packet is forwarded towards the sink. Finally, the section ends by comparing energy consumption in CCOF with conventional routing protocols commonly used. The Section 5.3 presents the performance evaluation of CCOF protocol.

5.2 Design of CCOF

In this section design of CCOF is presented based on same two assumptions namely all the nodes in the network are homogeneous and data generation rate in WSN is much lower compared to data delivery rate of the network. The design of CCOF is presented in two parts namely computation of expected cost and forwarding agreement among the nodes in forwarder list.

5.2.1 Computation of Expected Cost

The link cost for transmission of data from node u to $v_i \in N(u)$ include energy consumption for transmission at node u and reception at node v_i. The energy required for forwarding the data between directly connected nodes is given by Equation 5.1

$$\varepsilon = \varepsilon_t(u, v) + \varepsilon_r(u, v) \tag{5.1}$$

where $\varepsilon_t(u,v)$ and $\varepsilon_r(u,v)$ are transmit and receive energy for delivering a packet from node u to v. This link cost is used for determining the expected cost of any node u for forwarding the packet to the target node, as explained below. We compute the forwarder list and expected cost of node u based on the nodes in $N(u)$ whose expected cost forwarding to the sink is computed. The forwarder list of node u denoted $Pref(u)$ is a subset of $N(u)$. Given $Pref(u)$, let $Pref^{\star}(u)$ denote the increasingly sorted list based on the expected cost by each node in $Pref(u)$ to send data to sink. The $Pref^{\star}(u)$ has to be sorted in increasing order by the expected cost which is given by $Pref^{\star}(u) = \{v_1, v_2, \cdots, v_{|Pref(u)|}\}$ where $i < j \longrightarrow \zeta_{v_i} \leq \zeta_{v_j}$, where ζ_v is the expected cost. The forwarder list $Pref^{\star}(u)$ is the prefix set $N^{\star}(u)$, where $N^{\star}(u)$ is sorted in increasing order of expected cost for all nodes in $N(u)$. A node v_i is added to $Pref(u)$ if its cost is less than the expected cost of node u i.e. $\zeta_{v_i} < \zeta_u(Pref^{\star})$ otherwise discarded. The cost of transmitting the packet at u provided that atleast one node in $Pref^{\star}(u)$ successfully receives it is given by Equation 5.2.The nodes connectivity metric $CM(u)$ is used for calculating the expected cost of transmitting the packet and its successful reception by at least one node in $Pref^{\star}(u)$. The $CM(u)$ is algebraic connectivity [55] and is calculated as illustrated in Example 4.1 of Chapter 4 earlier.

$$\zeta_u^t(Pref^{\star}) = \frac{\varepsilon}{(1 - \Pi_{i=1}^{|Pref^{\star}|} p_{uv_i}) \times CM(u)} \tag{5.2}$$

The probability that node v_1 forwards the packet is $(1 - p_{uv_1})$ and its expected cost is ζ_{v_1}. Node v_2 will forward the packet with probability $p_{uv_1}(1 - p_{uv_2})$ and its cost is ζ_{v_2}. Multiple nodes in the forwarder list $Pref^{\star}(u)$ will forward the same packet independently, if there is no agreement among these nodes about which node should perform forwarding. Absence of agreement among the nodes in $Pref^{\star}(u)$ will avoid agreement cost, but will increase the network overhead due to multiple transmissions of the same packet. The expected cost for node u to forward the packet to sink in absence of such agreement is computed as given by Equation 5.3. The nodes connectivity metric $CM(u)$ in Equation 5.3 will increase the cost of forwarding through the nodes that have smaller connectivity value.

$$\zeta_u^f(Pref^\star) = \frac{\Sigma_{i=1}^{|Pref^\star|}(\Pi_{j=1,v_j\in N(v_i)}^{i-1} p_{uv_j})\cdot(1-p_{uv_i})\cdot\zeta_{v_i}}{(1-\Pi_{i=1}^{|Pref^\star|}p_{uv_i})\times CM(v_i)} \tag{5.3}$$

$$\zeta_u(Pref^\star) = \zeta_u^t(Pref^\star) + \zeta_u^f(Pref^\star) \tag{5.4}$$

In CCOF protocol, the expected cost of a sender to broadcast a packet if the current chosen forwarder list is given by Equation 5.4. Thus the expected cost of forwarding $\zeta_u(Pref^\star)$ is combination of two costs based on

1. Transmission of data packet to nodes in the forwarder list, given by Equation 5.2
2. Cost of relaying the packet by one or more nodes in the forwarder list to target node, given by Equation 5.3.

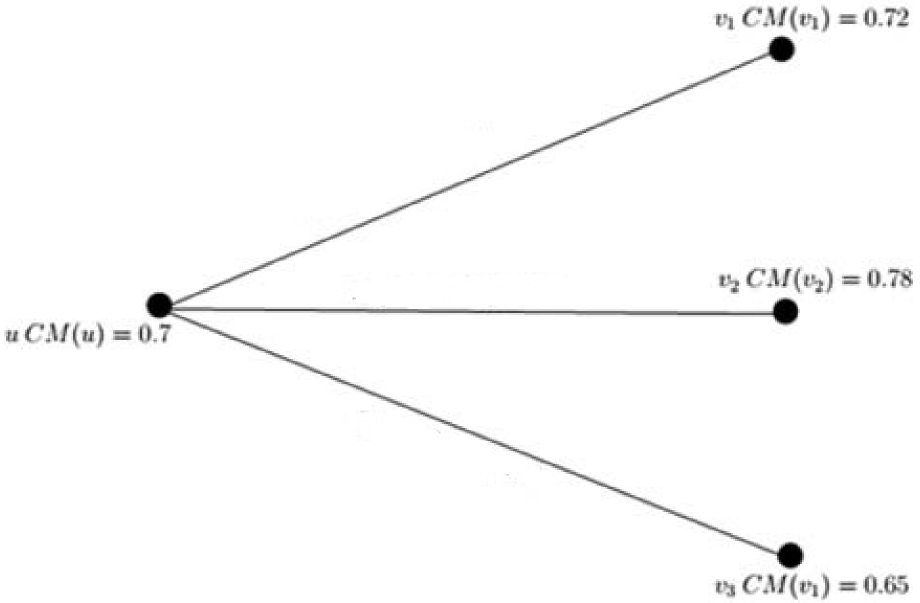

FIGURE 5.1: Example for construction of forwarder list

Example 5.1. *The forwarder list formation from the neighbour nodes is illustrated using an example shown in Figure 5.1. For node u,* $N(u) = \{v_1, v_2, v_3\}$*. For simplifying the calculations and to have understanding, the values for the parameters are assumed and shown in Table 5.1.*

Sr. No.	Parameter	Value
1	ε	1
2	Error probability p_{uv_i} denoted as p	0.5
3	$CM(u)$	0.7
4	$CM(v_1)$	0.72
5	$CM(v_2)$	0.78
6	$CM(v_3)$	0.65
7	ζ_{v_1}	1.0
8	ζ_{v_2}	1.5
9	ζ_{v_3}	3.0

TABLE 5.1: Values assumed for illustrating the formation of forwarder list

The calculations for the forwarder list for node u are explained below

- Let v_1 is added to $Pref(u)$. The expected cost $\zeta_u(Pref^\star)$ will be $(\frac{1}{1-p}(\frac{\varepsilon}{CM(u)} + \frac{(1-p)\zeta_{v_1}}{CM(v_1)})) = 4.24$.
- If the $Pref(u) = \{v_1, v_2\}$ then expected cost $\zeta_u(Pref^\star)$ will be $(\frac{1}{1-p^2}(\frac{\varepsilon}{CM(u)} + \frac{(1-p)\zeta_{v_1}}{CM(v_1)} + \frac{p(1-p)\zeta_{v_2}}{CM(v_2)})) = 3.47$.
- If the node v_3 is added to $Pref(u)$ then the expected cost will be $3.63 > 3.47$. So node v_3 is not added to the $Pref(u)$.

5.2.2 Forwarding Agreement in Forwarder List

The Equation 5.4 computes the expected cost of forwarding the packet through the nodes in the forwarder list. To avoid multiple forwarding of same packet by nodes in the forwarder list $Pref^\star(u)$, a small modification in IEEE 802.11 MAC protocol is proposed. The RTS-CTS mechanism in our MAC protocol is similar to that of IEEE 802.11 MAC protocol. After transmitting the data to $v_i \in Pref^\star(u)$, u waits for the ACK message. The first node in $Pref^{\star}(u)$ replies ACK immediately after Short Inter-Frame Spacing (SIFS). If the channel remains silent for interval after SIFS as shown in Figure 5.2, other nodes in $Pref^{\star}(u)$ start contending for sending the ACK. Instead of all other nodes in the $Pref^{\star}(u)$ replying the ACK message, only one node replies. The node that sends the ACK message becomes a relay node for forwarding the data to the sink. This reduces efforts for multiple data transmissions. Remaining nodes in the $Pref^{\star}(u)$ overhear the ACK message due to WBA [109] and then stop participating in process of becoming a possible relay node.

FIGURE 5.2: ACK for forwarding agreement from any node in forwarder list, if the first node has moved or failed

$$\begin{aligned} T_{reply} &= SIFS + \frac{T_{Pref^{\star}} \times \zeta_{v_i}^{norm} \times V_{v_i}}{1 - p_{uv_i}} \\ v_i &\in Pref^{\star}(u) \text{ for } i = 2 \cdots |Pref^{\star}(u)| \end{aligned} \tag{5.5}$$

Any node$v_i \in Pref^{\star}(u)$ for $i = 2 \cdots |Pref^{\star}(u)|$ sends ACK message to u with a delay calculated according to Equation 5.5. $T_{Pref^{\star}}$ is the maximum time delay for the nodes in $Pref^{\star}$. $\zeta_{v_i}^{norm}$ is the normalized expected cost of node v_i, p_{uv_i} is the link error probability and V_{v_i} is the normalised relative velocity. The normalisation for expected cost and velocity is done in the interval $[0.01, 1]$. The normalised expected cost prefers selecting the first node in the forwarder list $Pref^{\star}$. V_{v_i} indicates stability of a node in the mobile network. A node with smaller value for V_{v_i} is more favoured as it will not cause interruption in transmission. The node's with high mobility speeds are not preferred as they are associated with unstable links. The denominator in the Equation 5.5 refers to reliability of link. Hence, a link with lower expected cost and higher reliability is selected as the relay node. The back-off time for the nodes in

$Pref^{\star}$ is no greater than $SIFS + T_{Pref^{\star}}$. In case the first node in forwarder list has moved out at instance of receiving the data packet, other nodes in the forwarder list will send the ACK with a delay calculated according to Equation 5.5 and become the relay node. As against the traditional routing, retransmissions at the MAC layer will be avoided though the desired relay has moved. The probability that links to all the nodes in $Pref^{\star}$ fail simultaneously is much smaller than the probability of link failure to first node in the forwarder list $Pref^{\star}$. Therefore, other nodes in $Pref^{\star}$, at the cost of energy consumption for overhearing can improve the reliability and reduce the end-to-end delay. The energy consumption of overhearing can be mitigated by energy savings via avoiding retransmissions over a hostile or lost link. Alternative routing implemented at MAC layer, enables CCOF to forward data without solely relying on the network layer. This reduces the end-to-end delay as network layer efforts for alternative path computation. The network allocation vector (NAV) for IEEE 802.11 is updated at all nodes as given in Equation 5.6 to avoid inconsistency in DATA/ACK handshake.

$$NAV = NAV_{802.11} + T_{Pref^{\star}} \tag{5.6}$$

In the next subsection, comparison showing how energy consumption in CCOF is better compared to conventional routing protocols is presented.

5.2.3 Comparison of CCOF and Conventional Routing

In conventional routing protocols, packet retransmissions are performed if the desired relay node is not available due to its mobility, failure, or any other reason. In this comparison, we assume that all the link have same error probability denoted by p. In a conventional routing protocol total energy consumption cost ζ_{cr} of receiving one packet successfully by the desired relay following several retransmissions, theoretically infinite is calculated using Equation 5.7. The symbols $\varepsilon_s, \varepsilon_r$ and ε_t denote the energy consumption for sleep state, reception and transmission of a packet respectively. Also the ratio for energy consumption sleep state to reception state is $1 : 1.05$ [105] i.e. it can be observed that $\varepsilon_s \approx \varepsilon_r$. Using this approximation the

Equation 5.7 is simplified to determine the cost ζ_{cr} as combination of ε_r and ε_t given in the Equation 5.8.

$$\begin{aligned}\zeta_{cr} &= \varepsilon_s \cdot (|Pref^\star| - 1) + \varepsilon_r + (1-p)\cdot\varepsilon_t + \\ &\quad p(1-p)\cdot 2\varepsilon_t + p^2(1-p)\cdot 3\varepsilon_t + \cdots \\ &= \varepsilon_s \cdot (|Pref^\star| - 1) + \varepsilon_r + \Sigma_{i=1}^{\infty} p^{i-1}(1-p)\cdot i\cdot\varepsilon_t \\ &= \varepsilon_s \cdot (|Pref^\star| - 1) + \varepsilon_r + \tfrac{\varepsilon_t}{(1-p)}\end{aligned} \tag{5.7}$$

$$\zeta_{cr} = \varepsilon_r(|Pref^\star|) + \frac{\varepsilon_t}{(1-p)} \tag{5.8}$$

In CCOF, the probability that single transmission is successful is $\alpha = (1 - p^{|Pref^\star|})$. Let $m < |Pref^\star|$ be the number the nodes who successfully receive the packet. The total energy consumption for reception of packet by m nodes and the probability of successful reception by m nodes is given by Equation 5.9 and Equation 5.10 respectively. Assuming no retransmissions, the expected energy consumption for single transmission is given by Equation 5.11. Substituting the values for α, β and ζ_m from the above equations the ζ_1 can be determined as shown in Equation 5.12.

$$\zeta_m = (\varepsilon_t + m\cdot\varepsilon_r) \tag{5.9}$$

$$\beta = \binom{m}{|Pref^\star|} p^{(|Pref^\star|-m)}(1-p)^m \tag{5.10}$$

$$\zeta_1 = \frac{1}{\alpha}\cdot\Sigma_{m=1}^{|Pref^\star|}\zeta_m\cdot\beta \tag{5.11}$$

$$\begin{aligned}\zeta_1 &= \tfrac{1}{1-p^{|Pref^\star|}}\Sigma_{m=1}^{|Pref^\star|}(\varepsilon_t + m\cdot\varepsilon_r)\cdot\tbinom{m}{|Pref^\star|}p^{(|Pref^\star|-m)}(1-p)^m \\ &= \varepsilon_t + \varepsilon_r\tfrac{|Pref^\star|(1-p)}{(1-p^{|Pref^\star|})}\end{aligned} \tag{5.12}$$

If the node does several retransmissions, the expected energy consumption for successful packet reception by nodes in $Pref^\star$ is

$$\begin{aligned}\zeta_{ccof} &= \Sigma_{i=0}^{\infty}(\zeta_1 + i\cdot\varepsilon_t)(1-\alpha)^i\alpha \\ &= \zeta_1 + \varepsilon_t\tfrac{1-\alpha}{\alpha} \\ &= \varepsilon_t + \varepsilon_r\tfrac{|Pref^{\star}|(1-p)}{(1-p^{|Pref^{\star}|})} + \varepsilon_t\tfrac{p^{|Pref^{\star}|}}{(1-p^{|Pref^{\star}|})} \\ &= \varepsilon_t\tfrac{1}{(1-p^{|Pref^{\star}|})} + \varepsilon_r\tfrac{|Pref^{\star}|(1-p)}{(1-p^{|Pref^{\star}|})}\end{aligned} \tag{5.13}$$

From Figure 5.8 and Figure 5.13 it can be deduced that

$$\varepsilon_t\frac{1}{(1-p^{|Pref^{\star}|})} < \frac{\varepsilon_t}{(1-p)}, \varepsilon_r\frac{|Pref^{\star}|(1-p)}{(1-p^{|Pref^{\star}|})} < \varepsilon_r(|Pref^{\star}|) \tag{5.14}$$

Thus from the Equation 5.14, it can be observed that CCOF protocol consumes less energy compared to conventional routing algorithms due to considerable drop in the retransmissions of the packet. Moreover, the coordination among the nodes in the forwarder list minimizes the duplicates as well as routing overheads. Also this coordination among the nodes makes the protocol to perform well in mobile environments.

5.3 Simulation and Results

5.3.1 Simulation Model and Parameters

The simulation environment is same as considered in Chapter 4 Table 4.1. The mobile nodes move in a $750 \times 750m^2$ region for 50 seconds of simulation time. It is further presumed that all the nodes are homogeneous and have transmission range $40m$. The initial energy of node is assumed to be $12.3J$. The packet size of 512 bits and data rate is $150kbps$. Simulations have been performed by varying

- number of nodes and
- Speed of mobile nodes.

The numbers of nodes are varied from 100, 200, 300, and 400. The speed of mobile nodes varies from $5 - 25m/s$. The simulations are performed using network simulator 2 (NS2). Simulations have been done for CCOF, EEOR [82], DSDV [92], and AOMDV [83]. The results obtained are discussed and percentage improvements in CCOF presented are with respect to EEOR.

5.3.2 Performance Evaluation Based on Variation in Nodes

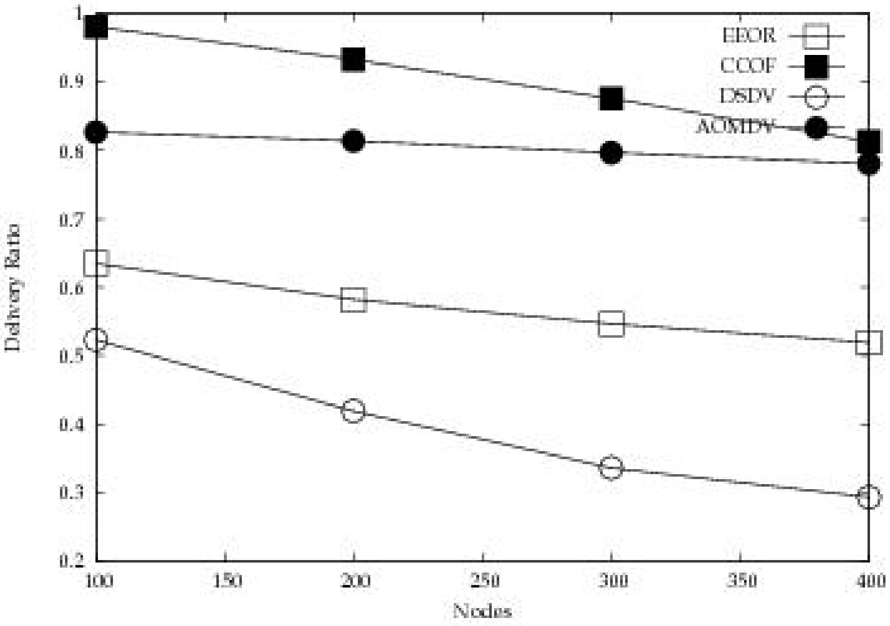

Figure 5.3: Packet delivery for varying number of nodes

In the first experiment, the number of nodes is varied as 100, 200, 300, and 400. The simulations are performed at constant mobility speed of $5m/s$. Figure 5.3 - Figure 5.6 show the simulator performance comparison of CCOF, EEOR [82], DSDV [92], and AOMDV [83]. The CCOF exhibits best performance, approximately 48% higher packet delivery function compared to EEOR as seen in Figure 5.3. This improvement is due to adaptiveness of CCOF to change in topology. AOMDV has better packet delivery compared to EEOR and DSDV due to multipath routing which mitigates the effect of node mobility. EEOR as well as DSDV protocol experiences lesser packet delivery as the established paths become frequently invalid due to mobility of nodes. Figure 5.4 shows that CCOF has 16% lesser routing overheads compared to EEOR. For all the protocols, network overheads increase with increase in node density. In

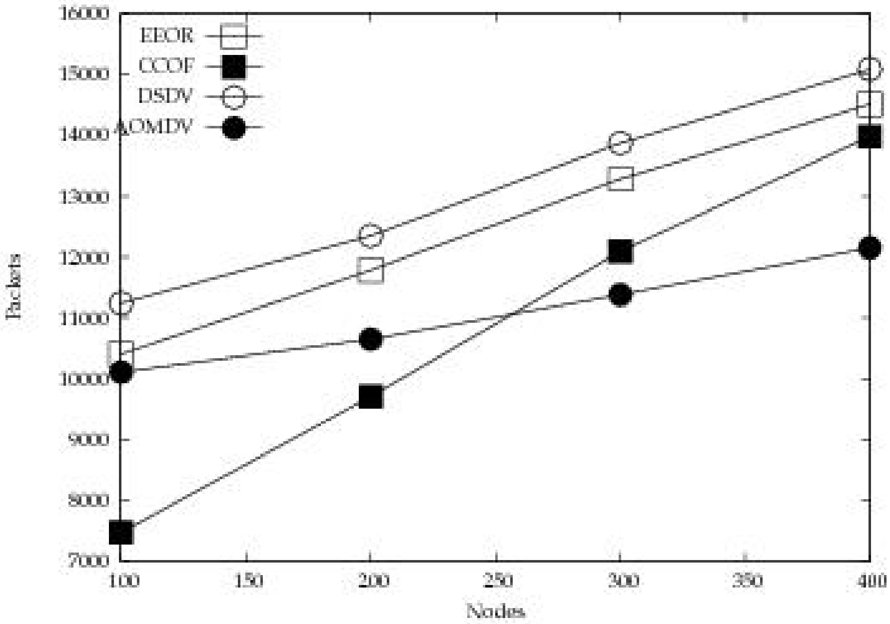

FIGURE 5.4: Routing overheads for varying number of nodes

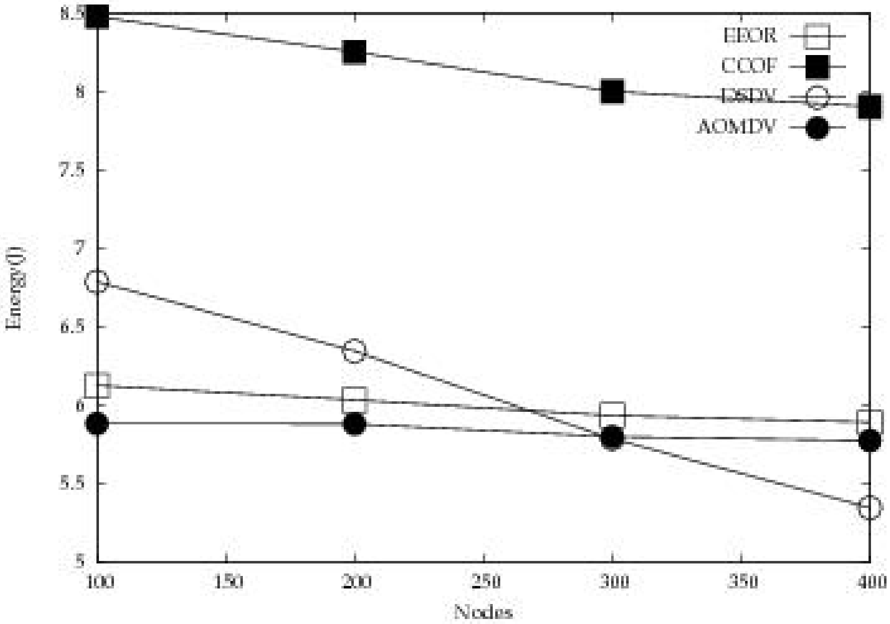

FIGURE 5.5: Residual energy for varying number of nodes

CCOF, backup nodes mitigate the effects of path breakages which reduce frequent re-computation of paths. In EEOR, moving nodes make the forwarder list invalid as time elapses. DSDV being proactive has to build the routing information frequently which increases the overheads. The alternative path availability in AOMDV makes

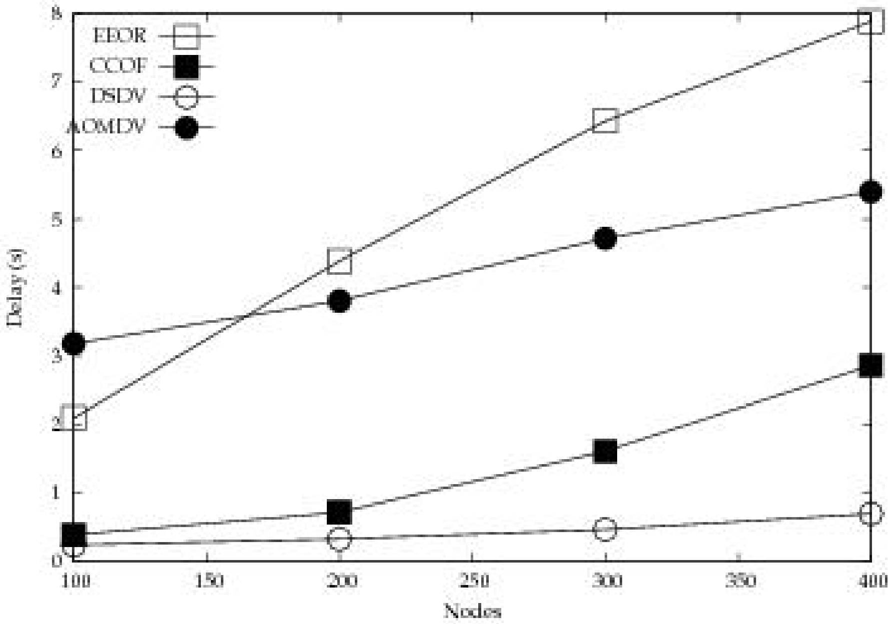

FIGURE 5.6: End-to-end for varying number of nodes

it least affected with increase in the number of nodes in the network. The CCOF has 26% more residual energy compared to EEOR as shown in Figure 5.5. The energy consumption for all the protocols increases with increase in node density. EEOR consumes more energy as it is a proactive algorithm and several paths break as time elapses, due to node mobility. In CCOF, the backup nodes perform the task of data forwarding in case the node on the computed path is not available. The energy consumption for AOMDV does not increase considerably with increase in node density as multiple paths forward the data packet without incurring much overhead. The end-to-end delay for CCOF is less by approximately 77% as shown in Figure 5.6. The EEOR [82] has more delay as moving nodes make the computed path invalid. In EEOR, the packet upon arrival is forwarded to a node with minimum cost in the forwarder list, but the forwarder list itself becomes outdated due to node mobility. Thus the packet has to wait for long time for computation of forwarder list. CCOF uses WBA[109] and so if the minimum cost node in the forwarder list has moved, backup nodes forward the packet thus minimize the packet waiting time. In DSDV [92], the routes are computed and stored so the data packets do not have to wait at the intermediate nodes. In AODMV, the routes are computed on demand so the packet has to wait long time before being forwarded.

5.3.3 Performance Evaluation Based on Variation in Speed

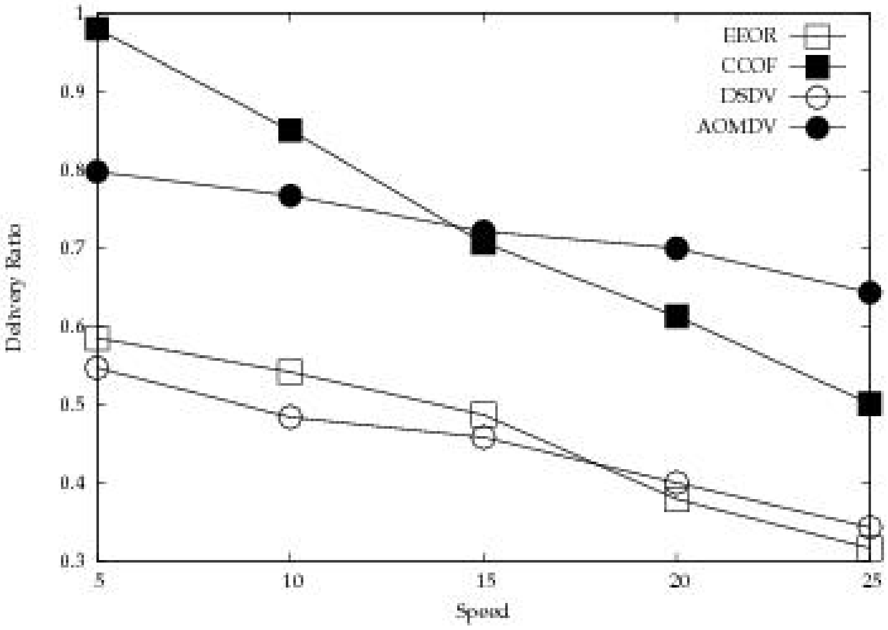

Figure 5.7: Packet delivery for varying speed

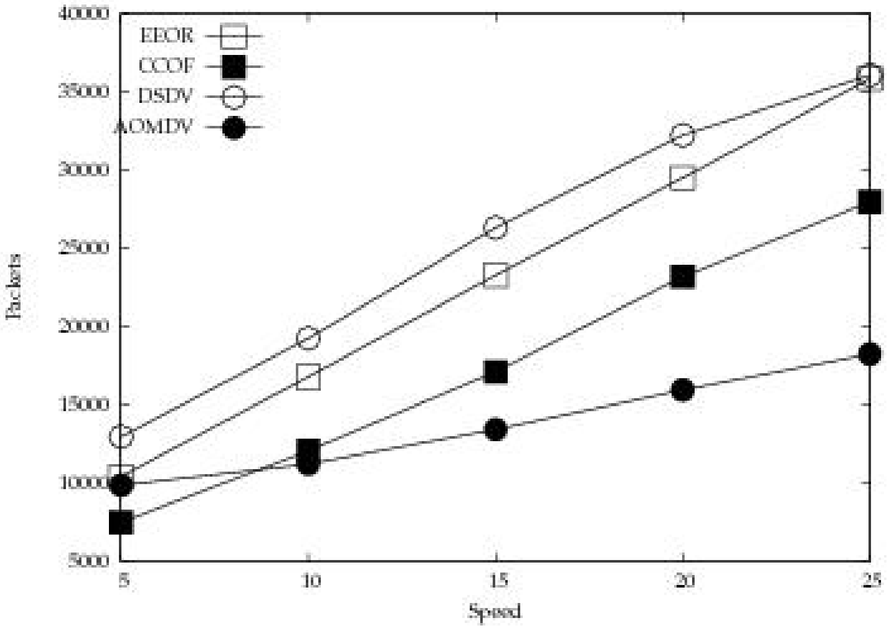

Figure 5.8: Routing overheads for varying speed

In the second experiment, the mobile speed of the nodes is varied as 5, 10, 15, 20 and $25m/s$. The number of nodes for the simulation are kept constant equal to 100. Figure 5.7 - Figure 5.10 show the simulation performance of CCOF, EEOR

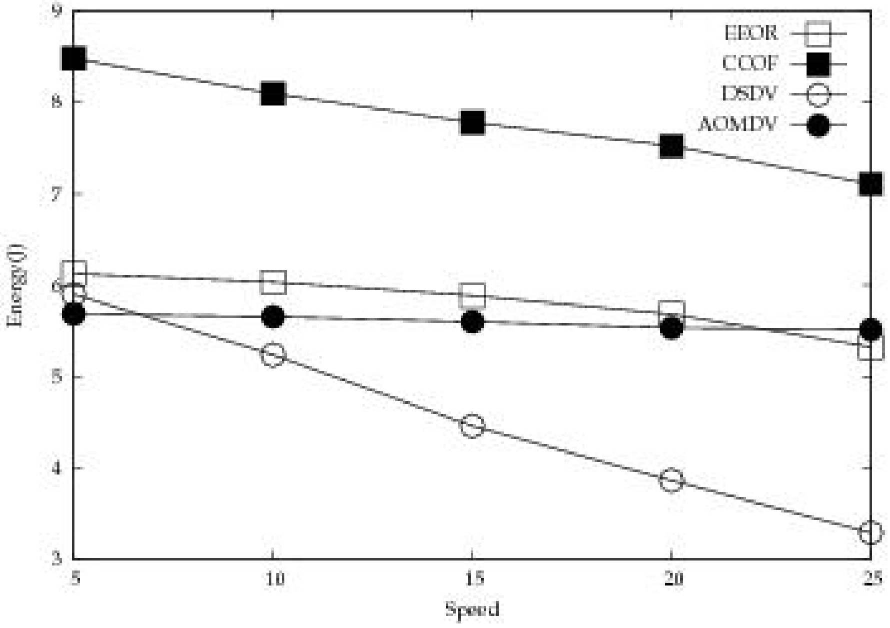

FIGURE 5.9: Residual energy for varying speed

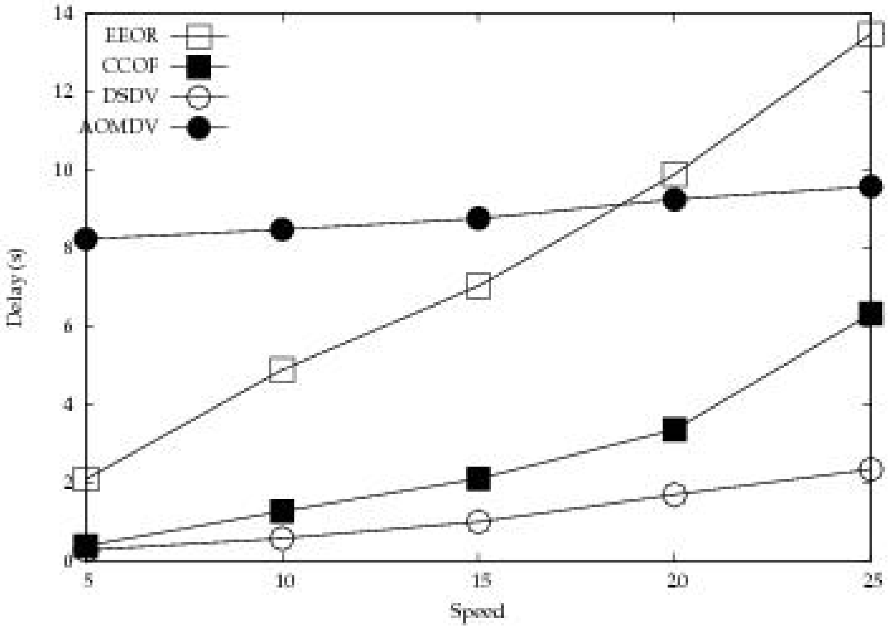

FIGURE 5.10: End-to-end for varying speed

[82], DSDV [92], and AOMDV [83] protocols at different mobility speeds. Figure 5.7 shows the packet delivery function for different node mobility speeds. Packet delivery function decreases with increase in speed as topology changes happen at higher rate for all protocols. The CCOF outperforms EEOR by approximately 45%. The

backup nodes react quickly to link breakages and forward the data through cooperation. In EEOR and DSDV, packet loss is more as these protocols do not establish backup paths. The packet delivery in CCOF degrades compared to AOMDV at higher mobility speeds due to higher availability of backup paths in AOMDV. The overheads in CCOF are approximately 26% lesser than EEOR as shown in Figure 5.8. In EEOR [82] moving nodes exchange more update messages to compute routes for forwarding. The backup nodes in CCOF help to forward the data without computation of paths. DSDV has highest network overheads as the topology change invalidates the computed routes. AOMDV reacts positively to topology changes as it has lower overheads among all the protocols. CCOF has 22% improved energy efficiency compared to EEOR as shown in Figure 5.9. Energy consumption increases with increase in node moving speed as rapid topology changes cause exchange of higher number of update messages to discover the paths. Cooperative forwarding using backup nodes in CCOF reduces consumption compared to EEOR. Higher overheads in DSDV increase the energy consumption. AOMDV has almost same energy consumption at all speeds as the number of route update messages do not increase with increase in speed. It is observed that CCOF gives optimum performance for energy consumption compared to all other protocols. Figure 5.10 shows that CCOF has 64% lesser end-to-end delay compared to EEOR. The end-to-end delay is less in CCOF as backup nodes forward the data, if the node on the original path has moved. In EEOR [82], if the node on the original path is not available then the packet has to wait till new routes are computed. DSDV protocol has the least delay among all the protocols as packets are forwarded without any delay. AOMDV has higher delay compared to DSDV and CCOF due its reactive nature.

The overall ranking of the four protocols investigated during the experimentation for four different parameters is shown in Table 5.2. The number of nodes considered is 400 and mobility speeds are categorized as low speeds for speed up to $15m/s$ and high speeds for speed exceeding $15m/s$. CCOF protocol gets mapped into top two ranks, thus becoming an optimal protocol for various conditions. It is seen that cross layer design of CCOF outperforms EEOR and is useful for mobile wireless sensor networks.

Protocols	Number of nodes = 400				Low speeds				High Speeds			
	a	b	c	d	a	b	c	d	a	b	c	d
DSDV	4	4	4	1	4	4	4	1	3	4	4	1
AOMDV	2	1	3	3	2	1	3	4	1	1	3	3
EEOR	3	3	2	4	3	3	2	3	4	3	2	4
CCOF	1	2	1	2	1	2	1	2	1	2	1	2

a: Packet delivery b: Routing overhead c:Residual energy d:End-to-end delay

TABLE 5.2: Ranking of protocols

5.4 Comparison of CBEEOR and CCOF

Sr. No.	Parameters	Performance in comparison with EEOR			
		Network Scalability		Node Mobility	
		CBEEOR	CCOF	CBEEOR	CCOF
1	Packet Delivery	$> 45 - 50$	> 48	> 30	> 45
2	Overhead	< 15	< 16	< 30	< 26
3	Energy Consumption	< 25	< 22	< 30	< 22

All values are in percentage.

TABLE 5.3: Performance of CBEEOR vs. CCOF in comparison with EEOR

It would be interesting to compare the performance of the two protocols CBEEOR and CCOF proposed in this thesis, particularly for three important parameters viz. packet delivery, overheads and energy consumption. Table 5.3 shows the performance comparison using the improvement values with respect to EEOR. Both the protocols give almost same performance in case of network scalability. For mobility variation CCOF gives slightly better packet delivery compared to CBEEOR. This is due to the fact that in CCOF the node velocity directly affects the priority assignment, which decides the selection of relay node and the backup node, in case the intended node has moved out. In CBEEOR, the node velocity only changes the time delay parameter for remedy nodes and therefore has weak linkage towards the successful packet delivery.

Thus it is expected that CCOF would give marginally better performance compared to CBEEOR, particularly in highly dynamic network environment. However, it would be interesting to look at computational time and efficiency aspects of the protocols, in actual field specific applications.

5.5 Conclusion

Thus, in this chapter the design and implementation of CCOF protocol for MWSNs is presented. It has been shown analytically that the proposed CCOF protocol provides much better improved energy performance compared to traditional routing protocols. The simulation results show that the performance of CCOF is much better compared to the EEOR protocol. The use of connectivity-based link cost estimation in determining the expected cost for forwarding results into an energy efficient forwarding scheme. The delay mechanism is implemented to have forwarding agreement among the nodes in the forwarder list, if the node first node has moved or failed. The delay mechanism implemented reduces overheads in the network by minimizing retransmissions. The CCOF exhibits improvements by 45% for packet delivery, 16% for overheads, and 22% for energy consumption compared to EEOR. Simulation results also show that the energy performance of CCOF is better when compared to AOMDV and DSDV, which more than substantiates the above analytical observation. The CCOF routing protocol can be enhanced to applications which require maintaining the network connectivity, while nodes are moving. Performance comparison in reference to EEOR of two new protocols namely CBEEOR and CCOF was presented and it is observed that CCOF performs marginally better than CBEEOR for packet delivery in node mobile environments. Both the CCOF and CBEEOR protocols show almost similar performance for overheads and energy consumption.

Similar assumptions, as made in design of CBEEOR, have been made into design of CCOF. However, there may be some applications or networks with very large number of nodes, wherein multiple nodes may have to transmit almost at the same time. Therefore, the performance of CCOF may need to be investigated in such applications and/ or network scenarios.

In the next chapter, a model for network lifetime prediction is presented. The protocols namely CCOF, EEOR and AOMDV are implemented on WSN consisting of Libelium waspmotes for measuring the network lifetime performance of these protocols on the available hardware devices.

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[1] This work has been published and details are: Mandar Karyakarte, Anil S. Tavildar and Rajesh Khanna "Connectivity-based Cross-layer Opportunistic Forwarding for MWSNs", Taylor and Francis IETE Journal of Research Feb 2015 ISSN 0377-2063 (Print), 0974-780X,SCIE indexed, Impact factor: 0.19, available online 13-04-2015.

Chapter 6

Network Lifetime Prediction and Measurement for MWSNs

Network lifetime is measure of time span for WSN network operation starting from deployment till its successful working for data collection for the phenomena being monitored. Network lifetime has been defined in many different ways [53], [9].Network Lifetime can be defined as time span measured from the deployment of network to the time instance when the network is considered to be non-functional. A network can be considered to be non-functional based on many parameters like; certain fraction of sensors become non-functional, expected link quality falls below certain pre-determined threshold, loss of coverage in some sectors or complete area being monitored, loss of connectivity, residual energy of nodes falls below minimum energy required for transmission etc. For example, from the energy dissipation viewpoint the network lifetime is defined as the time instance since the network deployment until the first node exhausts its energy below the minimum energy required for transmission under any channel condition. In this chapter a formulation for quantifying the network lifetime of MWSNs is presented in which non functionality based on residual energy of sensor nodes is considered.

The formulation for network lifetime prediction is presented in Section 6.1. Section 6.2 and Section 6.3 present the network lifetime estimation based on simulations and network lifetime measurement based on implementation over waspmotes [Libelium] respectively, followed by conclusion.

6.1 Network Lifetime Model

First Order Radio model [45] is considered as per the details given below

$$E_{Tx}(m,d) = E_{elec} \times m + \epsilon_{amp} \times m \times d^2 \tag{6.1}$$

$$E_{Rx}(m,d) = E_{elec} \times m \tag{6.2}$$

where $E_{Tx}(m,d)$ is energy consumption for transmitting m bit packet over distance d, $E_{Rx}(m,d)$ is energy consumed for receiving the same packet. E_{elec} is energy consumption to activate the transmitter or receiver circuitry which is $50nJ/bit$. ϵ_{amp} is constant energy for transmitter amplifier to communicate which is $100pJ/bit/m^2$ [45].

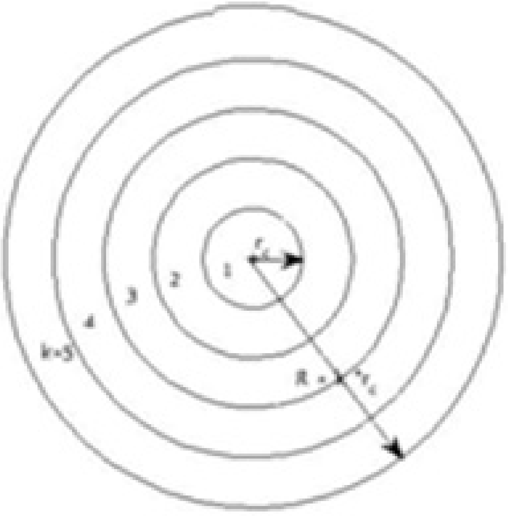

Figure 6.1: Division of network area

Just for the convenience of analysis, a simple theoretical network is assumed to be circular shape of radius R with sink S located at the centre denoted by (x_c, y_c). Further the network is partitioned in k concentric rings as shown in Figure 6.1 such that the innermost ring has radius r_c. Also the rings from $i = 2, 3, \cdots, k$ have their radius as $i \times r_c$. The ring k has its radius $R = k \times r_c$. The distance d_i is the euclidean distance of node i located at position(x_i, y_i) from the sink. The close vicinity of sink at time instance t denoted by $V_{s(t)}$ is a set of nodes which are within its transmission range r_c. $|V_{s(t)}|$ will give number of nodes in the close vicinity of sink at time instance t.

The expected network lifetime $\bar{E}(NLT)$ of the network is defined as, the time instance since deployment of the network until time at which the residual energy of the sensor node (E_n), for any node in the close vicinity of sink, falls below the amount of minimum energy required to transmit one single packet denoted by E_{min}. The expected network lifetime is given by Equation 6.3 [25].

$$\bar{E}(NLT) = \frac{E_0 - \bar{E}(E_w)}{P_c + \lambda \bar{E}(E_r)} \tag{6.3}$$

Where E_0: initial energy of any node at the time of network deployment, $\bar{E}(E_w)$: is expected wasted energy of nodes, P_c : is constant continuous power consumption of nodes during the idle state and $\bar{E}(E_r)$: is expected energy used while reporting for data collection. λ is defined as number of data collections per unit time. Wasted energy E_w is the residual energy in the sensor nodes, when the network becomes non-functional. As may be readily seen from the Equation 6.3, the lifetime can be maximized if both E_w and E_r are minimized. The residual energy E_i and minimum energy required for transmission of single packet E_{min}, together determine the state of sensor node i as given by Equation 6.4. If the value of η_i exceeds 1 than node continues to be operational in the network.

$$\eta_i = \frac{E_i}{E_{min}} \tag{6.4}$$

$$E_i(t) = E_n(t - t_c) - E_r \tag{6.5}$$

where

$$E_r = \begin{cases} E_{Tx}(m), & \text{if node } i \text{ is in last ring i.e. ring k} \\ E_{Tx}(m) + E_{Rx}(m), & \text{if node } i \text{ is in } 1 \cdots k-1 \text{ ring} \end{cases} \tag{6.6}$$

The sensor node $i \in V_{s(t)}$, will have to perform dual tasks of collecting and transmitting the data. Such node also has to forward the data received from the nodes located away from the sink. Such sensor node will therefore have much rapid energy drain compared to the sensor nodes located away from the sink. As the network is mobile and nodes will leave their places according to the node movement pattern, the number of nodes in the close vicinity of the sink will not remain constant during the operational lifetime of the network. It is therefore proposed to measure the rate of energy dissipation for all nodes $i \in V_{s(t)}$ given by Equation 6.7. γ_{i_p} is the rate of energy depletion of node i for the data reporting cycle p.The average value of rate of energy depletion of node i denoted by γ_i after l number of data reporting cycles is defined by Equation 6.8.

$$\gamma_{i_p} = \frac{de}{dt} = \frac{1}{t_c}|E_i(t) - E_i(t - t_c) \tag{6.7}$$

$$\gamma_i = \frac{\Sigma_{p=1}^{l} \gamma_{i_p}}{l} \tag{6.8}$$

The expected time required for the node i to reach its residual energy $E_i = E_{min}$ is predicted using the maximum value of γ_i, which will obviously will be a lower bound on $\bar{E}(NLT)$.

6.2 Network Lifetime Prediction using Simulations

6.2.1 Simulation Parameters

MWSN simulation is done using Network Simulator 2 (NS2). The simulations are carried over circular area of radius $71m$ with 36 sensor nodes. Each sensor node transmits the packet at an interval $t_c = 5$ *seconds*. The sink is assumed to be stationary and placed at the centre of simulation area. The sensor node deployment is considered random over the geographical area for simulation. The node mobility is synthesized using RWMM and GMMM mobility models as RWMM is one of the most commonly used random mobility models and GMMM gives node movements which are close real application environment. For GMMM, the memory level considered is $\alpha = 0.5$. The simulations are performed for 0.25, 2, 4 and $8m/s$ representing the typical speeds encountered in various low speed, medium speed and high speed applications in MWSNs. In this simulation, the initial energy E_0 includes the energy required only for communication of packets and is initialized as 5 Joules. Also the minimum energy E_{min} is the energy required for transmitting one single packet and in the simulation E_{min} considered is 0.000157 Joules. The packet size is set to 14 bytes.

For this simulation, most important performance parameter namely routing overhead defined as per the Equation 3.8 has been determined. Simulation period considered for this exercise was 2500 seconds. The performance was also simulated for zero mobility speed, which represents static WSN, for comparison purposes. Similar to studies of mobility models, even though MANET routing protocols are not generally suitable for MWSN, in this simulation for lifetime prediction, three protocols AODV [91], DSDV [92] and DSR [59] have been used just to understand and evaluate the lifetime prediction approach proposed. Actual estimation and measurements on practical WSN are attempted, using the latest protocol designed and proposed in Chapter 5. The results for routing overhead are indicated in Table 6.1, which would help to comment on the comparison for lifetime prediction proposed in this chapter.

	Node mobility speed in m/s				
	0	0.25	2	4	8
AODV GMMM	8.06	81.98	91.35	92.83	94.27
DSDV GMMM	61.73	66.82	74.41	79.35	84.23
DSR GMMM	1.34	5.84	11.01	14.82	18.28
AODV RWMM	8.06	70.39	89.52	92.35	93.89
DSDV RWMM	61.03	61.05	70.48	77.25	83.57
DSR RWMM	1.34	4.67	9.70	16.50	17.68

Table 6.1: Routing overheads

6.2.2 Discussion on Simulation Results

To determine the expected network lifetime $\bar{E}(NLT)$, as mentioned above the sink is assumed to be located at the centre of the network area. The region R_1 i.e. ring

$j = 1$ with radius $r_c = 30m$, the distance equal to single-hop distance in accordance with the transmit power setting of sensor nodes, is the region in the close vicinity of the sink. Nodes appearing more frequently in this region will have much higher energy dissipation compared to other nodes. The presence of various sensor nodes in the region R_1 at each data collection cycle over the entire simulation period of 2500 seconds considered for prediction of $\bar{E}(NLT)$. At the end of simulation, number of nodes appearing in the region R_1 has been tabulated as per the node serial number. Based on this, few nodes which are having presence in the region R_1 for large number of times have been identified. A plot of residual energy vs. time is drawn for all these nodes. It is observed that all these curves follow linear characteristics. The slope γ is calculated for this characteristic for each node and a node for which absolute γ value is highest is determined. This maximum value of γ is then used to determine $\bar{E}(NLT)$ by extrapolating the linear characteristics till residual energy falls equal to E_{min}. Following paragraph presents the results of these simulated evaluations of $\bar{E}(NLT)$.

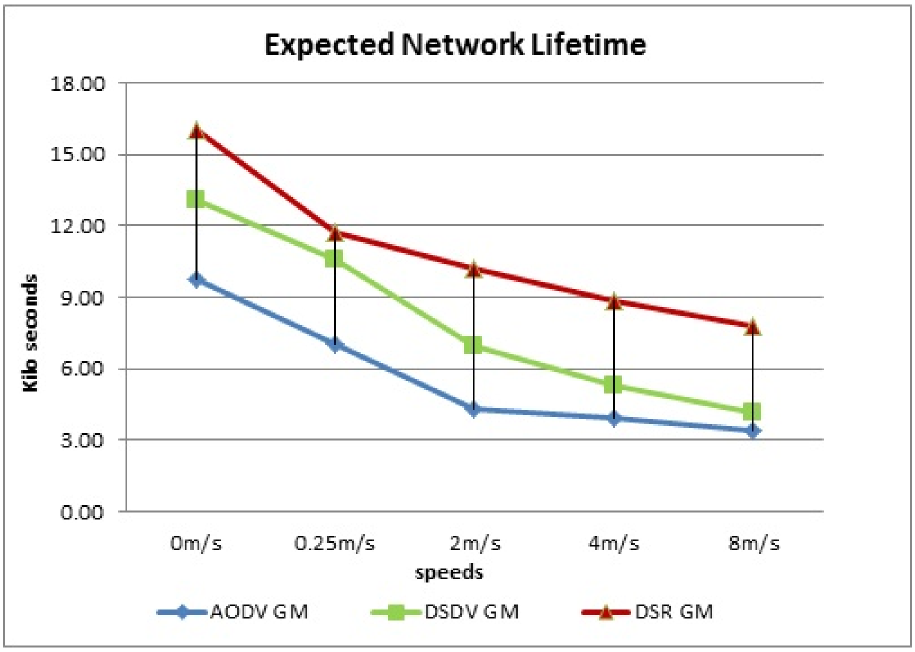

FIGURE 6.2: Expected Network Lifetime for GMMM

The Figure 6.2 and Figure 6.3 show the results for $\bar{E}(NLT)$. for GMMM and RWMM respectively. Lifetime is maximum for DSR [59] compared to DSDV [92] and AODV [91] for both GMMM and RWMM at all speeds. This is because the routing overhead as may be seen from Table 6.1 is considerably low for DSR [59].

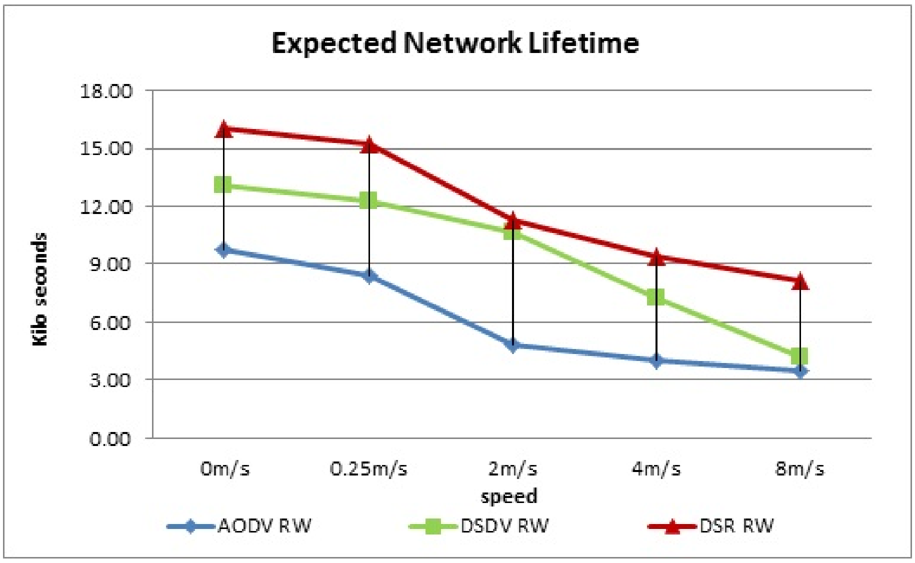

FIGURE 6.3: Expected Network Lifetime for RWMM

This reduces the energy required for data reporting, as lesser number of routing packets decreases the total energy consumption. $\bar{E}(NLT)$ decreases as the speed of the mobile nodes increases, for all three routing protocols and two mobility models considered which is due to increasing dynamism in the network topology induced by mobile nodes. Also comparing Figure 6.2 and Figure 6.3, it is observed that RWMM exhibits marginally better performance compared to GMMM, as it does not consider temporal correlation to determine next sortie speed and direction. Figure 6.2 and Figure 6.3 also compares the network lifetime of static WSNs and MWSNs. Static WSNs are simulated by setting the node velocity $v = 0$. The $\bar{E}(NLT)$ for static WSNs is higher than for MWSNs, this may be attributed to increased routing overhead in all routing protocols to mitigate the effect of node mobility in MWSNs.

6.2.3 Confidence level of Expected Network Lifetime prediction

The $\bar{E}(NLT)$ prediction is done using the residual energy level of nodes in the close vicinity of the sink i.e. region R_1. Probability distribution of the number of nodes in the region is calculated by measuring the presence of nodes in the region R_1 at the end of every data cycle for all 498 cycles. The typical probability density function (pdf) is shown in the Figure 6.4. Then the statistical average of this probability

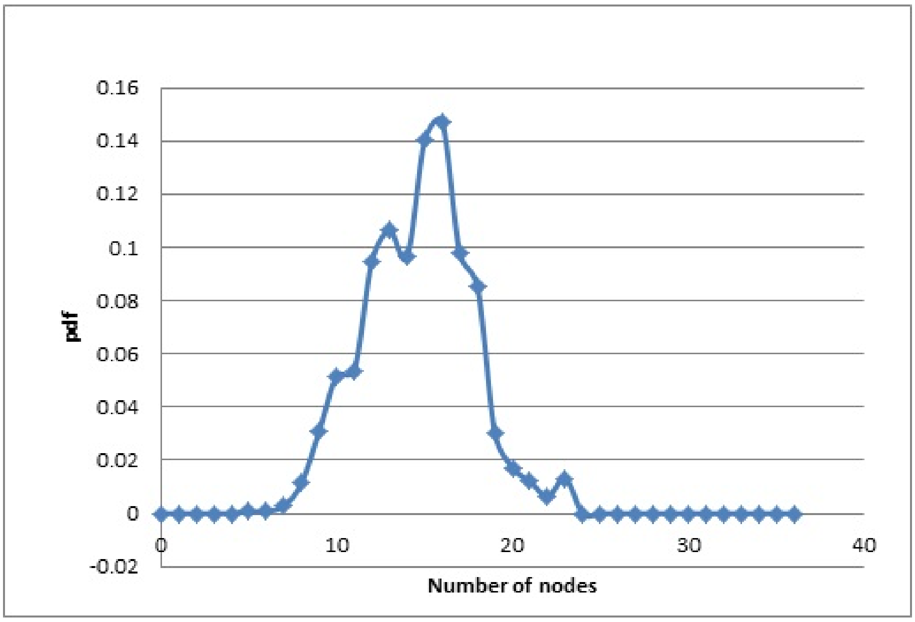

FIGURE 6.4: Distribution of nodes in Region R1 for DSR RWMM

distribution has been determined using $\mu_x = \Sigma_{i=0}^{36} x_i \times P(x_i)$. If the average number of nodes μ_x, in the region R_1 is close to half of the total number of nodes n, then it signifies that the confidence level of the prediction is very good. If $\mu_x \ll (n/2)$, confidence level is low, as very few nodes are present in R_1 for forwarding the data from the boundary nodes to the sink. If $\mu_x \gg (n/2)$, the confidence level can be considered to be excellent. Probabilistic average number of nodes denoted by μ_x, in the region R_1 for DSR [59] protocol for various speeds determined are shown in Table 6.2. This average is around 15, signifying the confidence level for the prediction of $\bar{E}(NLT)$ is good.

	Node mobility speed in m/s			
	0.25	2	4	8
DSR GMMM	14.2	14.5	15	14.69
DSR RWMM	16.28	14.65	14.68	14.94

TABLE 6.2: Probabilistic average number of nodes in R_1

In the next section, lifetime measurement using the waspmote devices and its comparison with predicted lifetime value using the approach presented in this section is discussed.

6.3 Network Lifetime Measurement

Figure 6.5: WSN network diagram

The purpose of measuring the network lifetime using the waspmote devices [Libelium] is to validate the network lifetime prediction approach presented in Section 6.2. WSN topology deployed using waspmotes is shown in Figure 6.5. The network consisted of 4 sensor nodes, 4 router nodes and a gateway. The gases board was attached to sensor nodes and routers only had communication board. Each sensor node used was capable of monitoring vehicular pollution in cities. The sensor board was equipped with temperature, humidity CO_2, CO, O_2 and O_3 gas sensors to monitor the levels. The photograph of gas board used is shown in Figure 6.6, and of communication board is shown in Figure 6.7. The communication was done using IEEE 802.15.4 standard in 2.4GHz ISM band. Each device can be powered with rechargeable batteries and a solar panel, making the system very autonomous. However, for measuring the lifetime the solar panel were not used. Instead batteries were fully charged to the maximum operating voltage. The sensor node, gas sensor board and sensors were placed inside an IP65 enclosure to be able to be mounted for monitoring the field. After deployment, constant readings of these parameters were taken.. With the help of GPRS data communication, all readings were delivered to the server where received data was processed and stored. The protocols CCOF, EEOR [82] and AOMDV [83] were programmed in each sensor node and router. For CCOF and EEOR only the cost estimation part was implemented. The forwarding agreement was not implemented as the medium access control layer in the hardware devices was IEEE 802.15.4. The network was kept operational until the battery level was reduced till no more packets could be sent. For experimental setup, we monitored the gases at every 90 seconds interval. However, practically the monitoring interval would be dynamic based on time of day. The details of node specification for waspmotes used are shown in Appendix A.

FIGURE 6.6: Gases sensor board for monitoring the vehicular pollution

6.3.1 Estimation of Lifetime for Experimental WSN Setup

The network lifetime prediction approach proposed in Section 6.2 was used to estimate the lifetime of the experimental WSN setup. The process followed for estimating the lifetime is elaborated below

1. The rate of battery energy depletion of each node for reduction of battery level from 100% i.e. $4.2V$ to 75% i.e $(4.2\breve{}(0.25 * (4.2\breve{}3.3)) = 3.975V$ for all the three protocols viz CCOF, EEOR [82] and AOMDV [83].

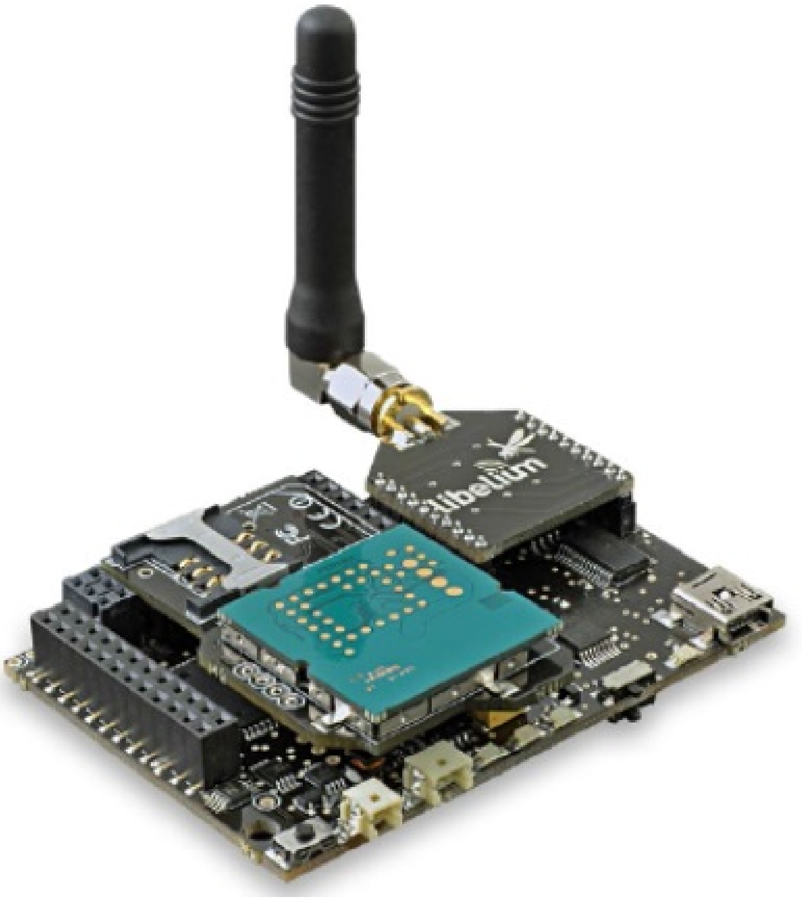

FIGURE 6.7: Waspmote communication board

2. Among all the nodes, a node which has highest rate of energy depletion dE/dT was considered for extrapolation.
3. This energy depletion rate is used to extrapolate the energy characteristics until the battery level reaches minimum operating value i.e. $3.3V$.

The results of estimation based on the above steps for network lifetime of experimental WSN setup is shown in Table 6.3

6.3.2 Measurement of Lifetime for Experimental WSN Setup

The network lifetime was actually measured for the experimental WSN by keeping the WSN setup operational until battery for the devices reached minimum operating

	Protocols		
	CCOF	EEOR	AOMDV
Lifetime Estimation	46	36	41

TABLE 6.3: Lifetime estimation in hours

voltage i.e. 3.3V. The Figure 6.8 shows the lifetime measurement for CCOF, EEOR [82] and AOMDV [83] routing protocols. The lifetime measured for CCOF, EEOR and AOMDV was 48 hours, 37 hours and 44 hours respectively as shown in Table 6.4.

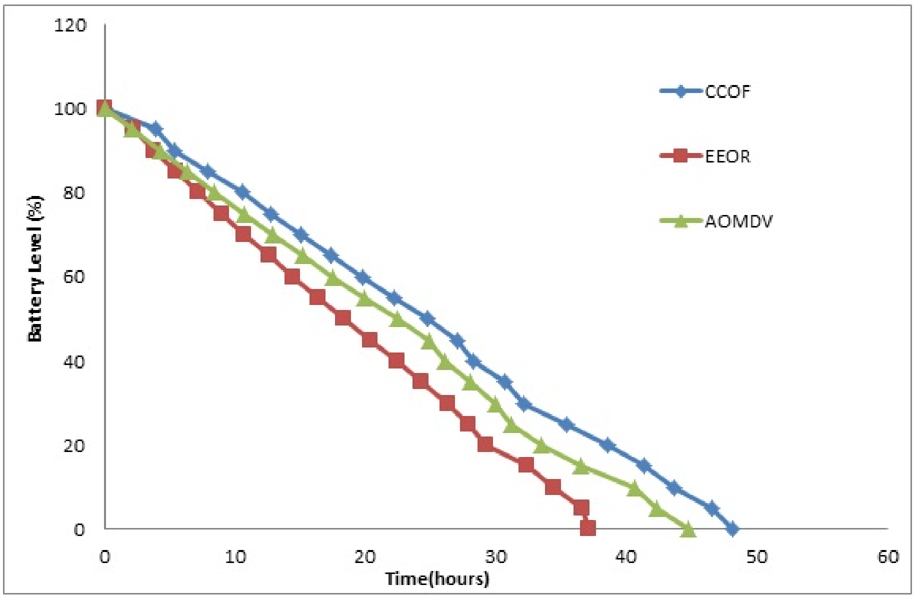

FIGURE 6.8: Measurement of lifetime using the experimental WSN.

	Protocols		
	CCOF	EEOR	AOMDV
Lifetime measurement	48	37	44

TABLE 6.4: Lifetime estimation in hours

The results for network lifetime estimation Table 6.3 and measurement Table 6.4 using experimental WSN setup help to validate the network lifetime prediction approach proposed in Section 6.2. It is difficult to compare the results for network lifetime estimation in terms of absolute values, for the simulation scenario Section 6.2.2, estimation Section 6.3.1 and measurement Section 6.3.2 of the experimental WSN setup due to the following reasons

1. The energy expenses in the simulation Section 6.2.2, only account for communication of packets whereas the in experimental setup Section 6.3, the battery energy is required to operate the communication board, gas board and the sensors.
2. The simulation Section 6.2.2 has random deployment of larger number of nodes compared to fixed predetermined deployment of only 8 nodes in the experimental setup Section 6.3.
3. In experimental setup Section 6.3, each sensor data is transmitted as separate packet to the base station i.e. 6 packets are received during each monitoring cycle.
4. The protocols used in the simulation Section 6.2.2 to understand the network lifetime prediction approach are different than the protocols used for validating the approach on experimental setup Section 6.3.

The better performance of CCOF as against EEOR and AOMDV for network lifetime measurement is in accordance with protocol ranking for residual energy done on the basis simulation results presented in Section 5. The results for simulations in Section 5 for residual energy and network lifetime measurement on experimental WSN for the protocols CCOF, EEOR and AOMDV cannot also be compared for absolute values due to the differences between the simulation environment and specification of WSN devices. However, the protocols show similar behavior and have same performance ranking in simulation environment and in the experimental WSN setup.

6.4 Conclusion

In this chapter, an approach for quantifying the expected network lifetime of MWSN based on residual energy level of mobile node is presented. The results show that there exists a strong correlation between the network lifetime and routing overhead. Also the speed of the mobile nodes affect the lifetime of the network. The quantification of network lifetime done is the lower bound i.e. maximum energy depletion rate is considered, and thus the actual lifetime of the network will always be on the higher side. Further, the confidence level in the predicted value of the network lifetime is also presented. CCOF protocol presented in Section 5 is implemented on waspmotes [Libelium] and its network lifetime was estimated, as well as measured. Further the lifetime was estimated and also measured for two protocols in the literature namely EEOR and AOMDV for benchmarking purpose of CCOF. The network lifetime measurements exhibit the similar behaviour to lifetime estimation approach for all the three protocols, thus validating the lifetime estimation approach. Also for all the three protocols, the lifetime measurement and residual energy in Section 5 show similar behaviour, thus validating the performance of the protocols both in simulation and experimental setup.

CCOF which is a improved version of CBEEOR is only considered for implementation on Libelium motes experimental setup; subsequent network lifetime estimation and measurement using the experimental setup. The energy consumption performance of CCOF and CBEEOR is similar. Therefore, it is felt that CBEEOR will also give similar results for network lifetime estimation and measurement.

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[1] This work has been published and details are: Mandar Karyakarte, Anil S Tavildar and Rajesh Khanna, "Network Lifetime Measurements for wireless sensor networks", ICEIT conference on advances in mobile communications, Networking and computing, April 2015.

Mandar Karyakarte, Anil S tavildar, Rajesh Khanna, "A Prediction of Network Lifetime and Effect of Node Deployment on Lifetime of MWSNs" IICEIT conference on advances in mobile communications, Networking and computing 27-28 Sept 2013.

Chapter 7

Conclusion and Future Scope

7.1 Summary of Conclusions

In this thesis two new opportunistic routing protocols namely connectivity based energy efficient opportunistic robust (CBEEOR) and connectivity-based cross-layer opportunistic forwarding (CCOF) have been designed. Simulations for these protocols have been done and performance has been compared with respect to recent opportunistic protocols proposed in the literature namely energy efficient opportunistic routing (EEOR)[82] and optimal opportunistic forwarding (OOF) [73].

The study presented in Chapter 3 related to mobility models helps to establish the correlation between node mobility and performance of MWSNs. In general, irrespective of choice of mobility model, increase in node mobility speed degrades MWSN performance.

The design of CBEEOR and its simulation is discussed in Chapter 4. The exhaustive simulation exercise shows that CBEEOR exhibits better performance of over 30% compared to EEOR [82] and 8% compared to OOF for packet delivery. Improvement of 25% compared to EEOR and 6% compared to OOF is observed for energy consumption. CBEEOR also shows improvements approximately in the range of $20 - 25\%$ compared to EEOR and $10 - 12\%$ compared to OOF for other parameters. Comparison of CBEEOR performance with OOF and improvements exhibited suggest that CBEEOR may be suitable even for intermittently connected networks.

As a further improvement on CBEEOR, design of one more energy efficient protocol namely CCOF with assumptions similar to CBEEOR has been proposed. The simulations exercise using same network scenario as in CBBEEOR are performed. The performance of CCOF is compared with EEOR [82] and two MANET routing protocols namely AOMDV [83] and DSDV [92] protocols. The CCOF exhibits improvements by 45% for packet delivery, 16% for overheads, and 22% for energy consumption compared to EEOR. The performance comparison of CBEEOR and CCOF is performed and it is observed that CCOF performs marginally better than CBEEOR for packet delivery particularly in node mobile environments. The simulations also show that the proposed CCOF protocol gives improved energy performance compared to traditional protocols AOMDV and DSDV for which benchmarking has been done.

An approach for lifetime prediction for WSN based on residual energy of the nodes has been included in Chapter 6. It is observed that there is a strong correlation between network lifetime and routing overhead of the protocol. The quantification of network lifetime done is the lower bound i.e. maximum energy depletion rate is considered, and thus the actual lifetime of the network will always be on the higher side. Further, the confidence level in the predicted value of the network lifetime is also discussed.

An attempt has been made to estimate network lifetime based on actual residual energy measurements done using a practical WSN experiment consisting of wsapmotes. However, there are several differences like actual energy consumption of the practical network compared to one considered in the network lifetime prediction approach. Network configuration used for prediction and measurement are different. Further the protocols used for prediction approach are essentially MANET routing protocols namely AODV [91], DSDV [92] and DSR [59]. The protocols used for implementation on waspmotes for estimation and measurement of network lifetime are namely CCOF, EEOR [82] and AOMDV [83]. As a result absolute values of lifetime based on theoretical analysis and practical measurements differ considerably. However, the behavioural nature of lifetime estimation and measurement show matching trends in accordance with the simulation results included for CCOF in Chapter 5.

The entire simulations and experimentation work in this thesis is based on one assumption that entire WSN considered comprises of homogeneous sensor nodes and data generation rates in MWSN are much lower then data delivery rates. Although this may be true for most of the individual applications of WSN, for larger networks involving several types of heterogeneous nodes, the protocol proposed in this thesis may require to be modified for working in the heterogeneous environment. Further the entire simulations for MWSN have been done considering synthesized mobility using the commonly used RWMM. However, in actual MWSN applications, the mobility may be different and accordingly mobility have to be synthesized using appropriate model. For both the new protocols namely CBEEOR and CCOF proposed in this thesis, improvements observed are mainly due to avoidance of multiple transmissions based on specific forwarding agreement incorporated in the 802.11 MAC layer. When these protocols are actually implemented on 802.11 based sensor devices, the 802.11 MAC layer framework may require appropriate modifications to make provision for the forwarding agreement.

7.1.1 Future Directions for Research

As indicated in Chapter 3 earlier, in this thesis mobility is synthesized using RWMM, which is extensively used by various researchers so far, thus helping in benchmarking of new protocols. However, GMMM model conforms to stochastic modelling and therefore synthesizes random node movement, which is very close to real-life applications. It is therefore suggested that node mobility with GMMM and routing using proposed CBEEOR and CCOF may be investigated as natural extension of the work to understand the performance of these protocols.

It would be interesting to investigate the computational complexity of the two protocols when the protocols are implemented on the practical WSN devices, as the sensor devices have limited computational capacity and memory. For both the protocols, it would be interesting to study the feasibility and performance of the proposed protocols for delay tolerant networks (DTN). DTNs are more intermittently connected and have different constraints like topology, mobility etc. compared to MWSNs. Real-time applications can be classified as hard, firm and soft real-time systems. Multipath and multicast communication [120], [11] are used for data forwarding in the time critical applications. Researchers can further enhance CCOF protocol to study its performance and possible enhancements, if necessary, for the real-time environment. Transmit power control helps to dynamically adjust the transmission power based on parameter like distance of next relay. Both, CBEEOR and CCOF simulations have been evaluated under fix transmit power and so researchers can further extend these protocols for a WSN containing devices with adjustable transmit power. CBEEOR and CCOF protocols need to be investigated for network with higher node density. In such network, there could be finite probability of simultaneous data transmission from number of nodes. Such scenario may have hidden/ exposed terminal problem, which will help in understanding behaviour and performance of the protocols

In Chapter 6, lifetime prediction and estimation is has been done using a network having simplified greatly network topology consisting of concentric rings with sink placed at centre. This can be extended to the network having its topology based on stochastic geometry.

In this thesis, opportunistic routing has been exploited to monitor randomly distributed phenomena. However, there could be applications that may require remote monitoring in specific regions or point of interest (PoI). The PoI may be individual or multiple, static or dynamic, based on presence of some pre-requisite condition like time of day. In such cases, the concept of OR can be extended for deployment of WSN to monitor PoI and appropriate protocols need to be designed for collecting data originating at PoI.

Appendix A

Waspmote Specifications

Sr. No.	Device Parameter	Specification
1	IEEE 802.15.4	$1mW$
2	Li-Ion rechargeable battery	$6600mAh$
3	Minimum operating voltage	$3.3V$
4	Maximum operating voltage	$4.4V$
5	On mode	$9mA$
6	Sleep mode	$62\mu A$
7	Waspmote Gases Board Power voltage	$3.3V$˘$5V$
8	Sensor power voltage	$5V$
9	Maximum current admitted by gases board	$200mA$
10	Humidity sensor	$0.5mA$ at $3.3V$ with response time 15 seconds
11	Temperature sensor	$12\mu A$ at $3.3V$ with response time 1.65 seconds
12	CO_2 sensor	$50mA$ at $5V$ with response time 90 seconds
13	CO sensor	$3mA$ at $5V$ with response time 1 second
14	Ozone	$34mA$ at $1.95 \sim 5V$ DC with response time 30 seconds
15	Molecular Oxygen	$0\mu A$ at $5.5 \sim 8.8mV$ with response time 15 seconds

Table A.1: Waspmote Specifications

Bibliography

[1] Akbas, M. and Turgut, D. (2010). Lightweight routing with qos support in wireless sensor and actor networks. In *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pages 1–5.

[2] Akkaya, K. and Younis, M. (2003). An energy-aware qos routing protocol for wireless sensor networks. In *Distributed Computing Systems Workshops, 2003. Proceedings. 23rd International Conference on*, pages 710–715.

[3] Akkaya, K. and Younis, M. (2005). A survey on routing protocols for wireless sensor networks. *Ad Hoc Networks*, 3:325–349.

[4] Akyildiz, I., Su, W., Sankarasubramaniam, Y., and Cayirci, E. (2002). A survey on sensor networks. *Communications Magazine, IEEE*, 40(8):102–114.

[5] Al-Karaki, J. and Kamal, A. (2004). Routing techniques in wireless sensor networks: a survey. *Wireless Communications, IEEE*, 11(6):6–28.

[6] Al-Otaibi, M. and Soliman, H. (2010). Efficient geographic routeless routing protocols with enhanced location update mechanism. *Int. J. Sen. Netw.*, 8(3/4):160–171.

[7] Arora, A., Dutta, P., Bapat, S., Kulathumani, V., Zhang, H., Naik, V., Mittal, V., Cao, H., Demirbas, M., Gouda, M., Choi, Y., Herman, T., Kulkarni, S., Arumugam, U., Nesterenko, M., Vora, A., and Miyashita, M. (2004). A line in the sand: A wireless sensor network for target detection, classification, and tracking. *Comput. Netw.*, 46(5):605–634.

[8] Arora, A., Ramnath, R., Ertin, E., Sinha, P., Bapat, S., Naik, V., Kulathumani, V., Zhang, H., Cao, H., Sridharan, M., Kumar, S., Seddon, N., Anderson, C.,

Herman, T., Trivedi, N., Nesterenko, M., Shah, R., Kulkami, S., Aramugam, M., Wang, L., Gouda, M., ri Choi, Y., Culler, D., Dutta, P., Sharp, C., Tolle, G., Grimmer, M., Ferriera, B., and Parker, K. (2005). Exscal: elements of an extreme scale wireless sensor network. In *Embedded and Real-Time Computing Systems and Applications, 2005. Proceedings. 11th IEEE International Conference on*, pages 102–108.

[9] Aziz, A., Sekercioglu, Y., Fitzpatrick, P., and Ivanovich, M. (2013). A survey on distributed topology control techniques for extending the lifetime of battery powered wireless sensor networks. *Communications Surveys Tutorials, IEEE*, 15(1):121–144.

[10] Bai, F. and Helmy, A. (2004). A survey of mobility models. *Wireless Adhoc Networks. University of Southern California, USA*, 206.

[11] Balakrishnan, M. and Birman, K. (2006). Reliable multicast for time-critical systems. In *First Workshop on Applied Software Reliability (WASR 2006)*. IEEE.

[12] Basagni, S., Chlamtac, I., Syrotiuk, V. R., and Woodward, B. A. (1998). A distance routing effect algorithm for mobility (dream). In *Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, MobiCom '98, pages 76–84, New York, NY, USA. ACM.

[13] Ben-Othman, J. and Yahya, B. (2010). Energy efficient and qos based routing protocol for wireless sensor networks. *J. Parallel Distrib. Comput.*, 70(8):849–857.

[14] bing CHENG, H., YANG, G., and jun HU, S. (2008). Nhrpa: a novel hierarchical routing protocol algorithm for wireless sensor networks. *The Journal of China Universities of Posts and Telecommunications*, 15(3):75 – 81.

[15] Biswas, S. and Morris, R. (2005). Exor: Opportunistic multi-hop routing for wireless networks. *SIGCOMM Comput. Commun. Rev.*, 35(4):133–144.

[16] Blum, B. M., He, T., Son, S., and Stankovic, J. A. (2003). Igf: A state-free robust communication protocol for wireless sensor networks. Technical report.

[17] Braginsky, D. and Estrin, D. (2002). Rumor routing algorthim for sensor networks. In *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, WSNA '02, pages 22–31, New York, NY, USA. ACM.

[18] Broch, J., Maltz, D. A., Johnson, D. B., Hu, Y.-C., and Jetcheva, J. (1998). A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, MobiCom '98, pages 85–97, New York, NY, USA. ACM.

[19] Bruno, R. and Nurchis, M. (2010). Survey on diversity-based routing in wireless mesh networks: Challenges and solutions. *Computer Communications*, 33(3):269 – 282.

[20] Camp, T., Boleng, J., and Davies, V. (2002). A survey of mobility models for ad hoc network research. *WIRELESS COMMUNICATIONS & MOBILE COMPUTING (WCMC): SPECIAL ISSUE ON MOBILE AD HOC NETWORKING: RESEARCH, TRENDS AND APPLICATIONS*, 2:483–502.

[21] Castro, M. C., Galluccio, L., Kassler, A., and Rametta, C. (2011). Opportunistic P2P communications in delay-tolerant rural scenarios. *EURASIP J. Wireless Comm. and Networking*, 2011.

[22] Chachulski, S., Jennings, M., Katti, S., and Katabi, D. (2007). Trading structure for randomness in wireless opportunistic routing. *SIGCOMM Comput. Commun. Rev.*, 37(4):169–180.

[23] Chen, M., Kwon, T., Mao, S., and Leung, V. C. M. (2009). Spatial-temporal relation-based energy-efficient reliable routing protocol in wireless sensor networks. *IJSNet*, 5(3):129–141.

[24] Chen, T.-S., Tsai, H.-W., Lo, Y.-H., and Chang, Y.-S. (2010). Mitigating query hotspots for wireless sensor networks. In *Proceedings of the 6th International Wireless Communications and Mobile Computing Conference*, IWCMC '10, pages 94–98, New York, NY, USA. ACM.

[25] Chen, Y. and Zhao, Q. (2005). On the lifetime of wireless sensor networks. *IEEE COMMUNICATIONS LETTERS*, 9(11):976–978.

[26] Cheng, L., Niu, J., Cao, J., Das, S., and Gu, Y. (2014). Qos aware geographic opportunistic routing in wireless sensor networks. *Parallel and Distributed Systems, IEEE Transactions on*, 25(7):1864–1875.

[27] Chong, C.-Y. and Kumar, S. (2003). Sensor networks: evolution, opportunities, and challenges. *Proceedings of the IEEE*, 91(8):1247–1256.

[28] Chowdhury, K. and Di Felice, M. (2009). Search: A routing protocol for mobile cognitive radio ad-hoc networks. In *Sarnoff Symposium, 2009. SARNOFF '09. IEEE*, pages 1–6.

[29] Chu, M., Haussecker, H., Zhao, F., Chu, M., Haussecker, H., and Zhao, F. (2002). Scalable information-driven sensor querying and routing for ad hoc heterogeneous sensor networks. *International Journal of High Performance Computing Applications*, 16.

[30] Clausen, T. and Jacquet, P. (2003). Optimized link state routing protocol (olsr).

[31] Cordeiro, C. D. M. and Agrawal, D. P. (2006). *Ad Hoc & Sensor Networks: Theory And Applications*. World Scientific Publishing Co., Inc., River Edge, NJ, USA.

[32] De Couto, D. S. J., Aguayo, D., Bicket, J., and Morris, R. (2003). A high-throughput path metric for multi-hop wireless routing. In *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking*, MobiCom '03, pages 134–146, New York, NY, USA. ACM.

[33] Dijkstra, E. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, 1(1):269–271.

[34] Draves, R., Padhye, J., and Zill, B. (2004). Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking*, MobiCom '04, pages 114–128, New York, NY, USA. ACM.

[35] Estrin, D., Girod, L., Pottie, G., and Srivastava, M. (2001). Instrumenting the world with wireless sensor networks. In *Acoustics, Speech, and Signal Processing, 2001. Proceedings. (ICASSP '01). 2001 IEEE International Conference on*, volume 4, pages 2033–2036 vol.4.

[36] Estrin, D., Govindan, R., Heidemann, J., and Kumar, S. (1999). Next century challenges: Scalable coordination in sensor networks. In *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, MobiCom '99, pages 263–270, New York, NY, USA. ACM.

[37] Faruque, J. and Helmy, A. (2003). Gradient-based routing in sensor networks. *Mobile Computing and Communications Review (MC2R).*

[38] Felemban, E., Lee, C.-G., and Ekici, E. (2006). Mmspeed: multipath multi-speed protocol for qos guarantee of reliability and. timeliness in wireless sensor networks. *Mobile Computing, IEEE Transactions on*, 5(6):738–754.

[39] Fiedler, M. (1973). Algebraic connectivity of graphs. *Czechoslovak Mathematical Journal*, 23(2):298–305.

[40] Füßler, H., Widmer, J., Käsemann, M., Mauve, M., and Hartenstein, H. (2003). Contention-based forwarding for mobile ad hoc networks.

[41] Ge, W., Zhang, J., and Xue, G. (2008). Joint clustering and optimal cooperative routing in wireless sensor networks. In *Communications, 2008. ICC '08. IEEE International Conference on*, pages 2216–2220.

[42] Haas, Z. (1997). A new routing protocol for the reconfigurable wireless networks. In *Universal Personal Communications Record, 1997. Conference Record., 1997 IEEE 6th International Conference on*, volume 2, pages 562–566 vol.2.

[43] Handy, M., Haase, M., and Timmermann, D. (2002). Low energy adaptive clustering hierarchy with deterministic cluster-head selection. In *Mobile and Wireless Communications Network, 2002. 4th International Workshop on*, pages 368–372.

[44] Hedetniemi, S. M., Hedetniemi, S. T., and Liestman, A. L. (1988). A survey of gossiping and broadcasting in communication networks. *Networks*, 18(4):319–349.

[45] Heinzelman, W., Chandrakasan, A., and Balakrishnan, H. (2002). An application-specific protocol architecture for wireless microsensor networks. *Wireless Communications, IEEE Transactions on*, 1(4):660–670.

[46] Heinzelman, W. R., Kulik, J., and Balakrishnan, H. (1999). Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of*

the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking, MobiCom '99, pages 174–185, New York, NY, USA. ACM.

[47] Hill, J., Szewczyk, R., Woo, A., Hollar, S., Culler, D., and Pister, K. (2000). System architecture directions for networked sensors. *SIGPLAN Not.*, 35(11):93–104.

[48] Hsu, C.-J., Liu, H.-I., and Seah, W. (2009). Economy: A duplicate free opportunistic routing. In *Proceedings of the 6th International Conference on Mobile Technology, Application & Systems*, Mobility '09, pages 17:1–17:6, New York, NY, USA. ACM.

[49] Huang, X., Zhai, H., and Fang, Y. (2008). Robust cooperative routing protocol in mobile wireless sensor networks. *Wireless Communications, IEEE Transactions on*, 7(12):5278–5285.

[50] Hwang, J., Shin, C., and Yoe, H. (2010). Study on an agricultural environment monitoring server system using wireless sensor networks. *Sensors (Basel, Switzerland)*, 10(12):11189–211.

[51] Intanagonwiwat, C., Govindan, R., and Estrin, D. (2000). Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, MobiCom '00, pages 56–67, New York, NY, USA. ACM.

[52] Issariyakul, T. and Hossain, E. (2008). *Introduction to Network Simulator NS2*. Springer Publishing Company, Incorporated, 1 edition.

[53] Jagyasi, B., Dey, B., Merchant, S., and Desai, U. (2006). Weighted aggregation scheme with lifetime-accuracy tradeoff in wireless sensor network. In *Intelligent Sensing and Information Processing, 2006. ICISIP 2006. Fourth International Conference on*, pages 31–36.

[54] Jain, M., Patle, V. K., and Kumar, S. (2015). Performance of mobility models with different routing protocols by using simulation tools for wsn: A review. *International Journal of Advanced Research in Computer and Communication Engineering*, 4(1):57–61.

[55] Jamakovic, A. and Uhlig, S. (2007). On the relationship between the algebraic connectivity and graph's robustness to node and link failures. In *Next Generation Internet Networks, 3rd EuroNGI Conference on*, pages 96–102.

[56] Jia, Y., Zhao, L., and Ma, B. (2008). A hierarchical clustering-based routing protocol for wireless sensor networks supporting multiple data aggregation qualities. *Int. J. Sen. Netw.*, 4(1/2):79–91.

[57] Johnson, D. and Maltz, D. (1996a). Dynamic source routing in ad hoc wireless networks. In Imielinski, T. and Korth, H., editors, *Mobile Computing*, volume 353 of *The Kluwer International Series in Engineering and Computer Science*, pages 153–181. Springer US.

[58] Johnson, D. B. and Maltz, D. A. (1996b). Dynamic source routing in ad hoc wireless networks. In *Mobile Computing*, pages 153–181. Kluwer Academic Publishers.

[59] Johnson, D. B., Maltz, D. A., and Broch, J. (2001). Dsr: The dynamic source routing protocol for multi-hop wireless ad hoc networks. In *In Ad Hoc Networking, edited by Charles E. Perkins, Chapter 5*, pages 139–172. Addison-Wesley.

[60] Koutsonikolas, D., Wang, C.-C., and Hu, Y. (2010). Ccack: Efficient network coding based opportunistic routing through cumulative coded acknowledgments. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–9.

[61] Kulik, J., Heinzelman, W., and Balakrishnan, H. (2002). Negotiation-based protocols for disseminating information in wireless sensor networks. *Wirel. Netw.*, 8(2/3):169–185.

[62] Kulkarni, N., Prasad, R., Cornean, H., and Gupta, N. (2011). Performance evaluation of aodv, dsdv amp; dsr for quasi random deployment of sensor nodes in wireless sensor networks. In *Devices and Communications (ICDeCom), 2011 International Conference on*, pages 1–5.

[63] Larsson, P. (2001). Selection diversity forwarding in a multihop packet radio network with fading channel and capture. *SIGMOBILE Mob. Comput. Commun. Rev.*, 5(4):47–54.

[64] Larsson, P. and Johansson, N. (2005). Multiuser diversity forwarding in multihop packet radio networks. In *Wireless Communications and Networking Conference, 2005 IEEE*, volume 4, pages 2188–2194 Vol. 4.

[65] Laufer, R., Dubois-Ferriere, H., and Kleinrock, L. (2009). Multirate anypath routing in wireless mesh networks. In *INFOCOM 2009, IEEE*, pages 37–45.

[66] Li, L. and Halpern, J. (2001). Minimum-energy mobile wireless networks revisited. In *Communications, 2001. ICC 2001. IEEE International Conference on*, volume 1, pages 278–283 vol.1.

[67] Li, Q., Aslam, J., and Rus, D. (2001). Hierarchical power-aware routing in sensor networks. In *In Proceedings of the DIMACS Workshop on Pervasive Networking.*

[68] Liang, B. and Haas, Z. (1999). Predictive distance-based mobility management for pcs networks. In *INFOCOM '99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 3, pages 1377–1384 vol.3.

[Libelium] Libelium. Waspmote - Wireless Sensor Networks 802.15.4 ZigBee Mote - Open Source Sensor Device | Libelium.

[70] Lin, Y., Li, B., and Liang, B. (2008). Codeor: Opportunistic routing in wireless mesh networks with segmented network coding. In *Network Protocols, 2008. ICNP 2008. IEEE International Conference on*, pages 13–22.

[71] Lin, Y., Liang, B., and Li, B. (2010). Slideor: Online opportunistic network coding in wireless mesh networks. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–5.

[72] Lindsey, S. and Raghavendra, C. (2002). Pegasis: Power-efficient gathering in sensor information systems. In *Aerospace Conference Proceedings, 2002. IEEE*, volume 3, pages 3–1125–3–1130 vol.3.

[73] Liu, C. and Wu, J. (2012). On multicopy opportunistic forwarding protocols in nondeterministic delay tolerant networks. *Parallel and Distributed Systems, IEEE Transactions on*, 23(6):1121–1128.

[74] Liu, J. and Hong, X. (2009). An online energy-efficient routing protocol with traffic load prospects in wireless sensor networks. *Int. J. Sen. Netw.*, 5(3):185–197.

[75] Liu, K. and Abu-Ghazaleh, N. B. (2008). Aligned virtual coordinates for greedy geometric routing in wsns. *IJSNet*, 3(4):252–265.

[76] Liu, L., Wang, Z., and Zhou, M. (2007). Energy-efficient cooperative routing for wireless sensor networks using space time block code. In *Systems, Man and Cybernetics, 2007. ISIC. IEEE International Conference on*, pages 2837–2842.

[77] ludwig Wenning, B., Lukosius, A., Timm-giel, A., Görg, C., and Tomic, S. (2008). Opportunistic distance-aware routing in multi-sink mobile wireless sensor networks. In *ICT-MobileSummit 2008, Conference Proceedings, Stockholm.*

[78] Luo, H., Ye, F., Cheng, J., Lu, S., and Zhang, L. (2005). Ttdd: Two-tier data dissemination in large-scale wireless sensor networks. *Wireless Networks*, 11(1-2):161–175.

[79] Mainwaring, A., Culler, D., Polastre, J., Szewczyk, R., and Anderson, J. (2002). Wireless sensor networks for habitat monitoring. In *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, WSNA ’02, pages 88–97, New York, NY, USA. ACM.

[80] Manjeshwar, A. and Agrawal, D. P. (2001). Teen: A routing protocol for enhanced efficiency in wireless sensor networks. In *in Proc. IPDPS 2001 Workshops.*

[81] Manjeshwar, A. and Agrawal, D. P. (2002). Apteen: A hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks. In *Parallel and Distributed Processing Symposium, Proceedings International*, pages 195–202.

[82] Mao, X., Tang, S., Xu, X., Li, X.-Y., and Ma, H. (2011). Energy-efficient opportunistic routing in wireless sensor networks. *Parallel and Distributed Systems, IEEE Transactions on*, 22(11):1934–1942.

[83] Marina, M. K. and Das, S. R. (2006). Ad hoc on-demand multipath distance vector routing. *Wireless Communications and Mobile Computing*, 6(7):969–988.

[84] Munir, S., Ren, B., Jiao, W., Wang, B., Xie, D., and Ma, J. (2007). Mobile wireless sensor network: Architecture and enabling technologies for ubiquitous computing. In *Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on*, volume 2, pages 113–120.

[85] Murthy, S. and Garcia-Luna-Aceves, J. J. (1996). An efficient routing protocol for wireless networks. *Mob. Netw. Appl.*, 1(2):183–197.

[86] Muruganathan, S., Ma, D., Bhasin, R., and Fapojuwo, A. (2005). A centralized energy-efficient routing protocol for wireless sensor networks. *Communications Magazine, IEEE*, 43(3):S8–13.

[87] Ogier, R., Templin, F., and Lewis, M. (2004). Topology dissemination based on reverse-path forwarding (tbrpf).

[88] Pahal, S., Singh, B., and Arora, A. (2013). A prediction based handover trigger in overlapped heterogeneous wireless networks. In *Signal Processing, Computing and Control (ISPCC), 2013 IEEE International Conference on*, pages 1–6. IEEE.

[89] Panigrahi, B., De, S., and Luk, J.-D. L. S. (2009). A greedy minimum energy consumption forwarding protocol for wireless sensor networks. In *Proceedings of the First International Conference on COMmunication Systems And NETworks*, COMSNETS'09, pages 58–63, Piscataway, NJ, USA. IEEE Press.

[90] Park, V. D. and Corson, M. S. (1997). A highly adaptive distributed routing algorithm for mobile wireless networks. In *Proceedings of the INFOCOM '97. Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Driving the Information Revolution*, INFOCOM '97, pages 1405–, Washington, DC, USA. IEEE Computer Society.

[91] Perkins, C., Belding-Royer, E., and Das, S. (2003). Ad hoc on-demand distance vector (aodv) routing.

[92] Perkins, C. E. and Bhagwat, P. (1994). Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. *SIGCOMM Comput. Commun. Rev.*, 24(4):234–244.

[POSTECH] POSTECH. Mobile networking laboratory, dept of computer science and engineering, http://monet.postech.ac.kr/research.html. Accessed October 2015.

[94] Pottie, G. J. and Kaiser, W. J. (2000). Wireless integrated network sensors. *Commun. ACM*, 43(5):51–58.

[95] Qi, H., Iyengar, S., and Chakrabarty, K. (2001). Distributed sensor networks—a review of recent research. *Journal of the Franklin Institute*, 338(6):655 – 668.

[96] Qiang, D., Shanzhi, C., Dongliang, X., and Bo, H. (2009). Duplicate-aware opportunistic routing for multi-hop wireless networks. In *Broadband Network Multimedia Technology, 2009. IC-BNMT '09. 2nd IEEE International Conference on*, pages 80–84.

[97] Rodoplu, V. and Meng, T. H. (1999). Minimum energy mobile wireless networks. *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, 17(8):1333–1344.

[98] Royer, E., Melliar-Smith, P., and Moser, L. (2001). An analysis of the optimum node density for ad hoc mobile networks. In *Communications, 2001. ICC 2001. IEEE International Conference on*, volume 3, pages 857–861 vol.3.

[99] Rozner, E., Seshadri, J., Mehta, Y., and Qiu, L. (2009). Soar: Simple opportunistic adaptive routing protocol for wireless mesh networks. *Mobile Computing, IEEE Transactions on*, 8(12):1622–1635.

[100] Sadagopan, N., Krishnamachari, B., and Helmy, A. (2005). Active query forwarding in sensor networks. *Journal of Ad Hoc Networks*, 3:91–113.

[101] Schwiebert, L., Gupta, S. K., and Weinmann, J. (2001). Research challenges in wireless networks of biomedical sensors. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, MobiCom '01, pages 151–165, New York, NY, USA. ACM.

[102] Sha, K., Du, J., and Shi, W. (2006). Wear: a balanced, fault-tolerant, energy-aware routing protocol in wsns. *Int. J. Sen. Netw.*, 1(3/4):156–168.

[103] Sohrabi, K., Gao, J., Ailawadhi, V., and Pottie, G. (2000). Protocols for self-organization of a wireless sensor network. *Personal Communications, IEEE*, 7(5):16–27.

[104] Sohraby, K., Minoli, D., and Znati, T. (2007). *Wireless Sensor Networks: Technology, Protocols, and Applications*. John Wiley and Sons.

[105] Stemm, M. and Katz, R. H. (1997). Measuring and reducing energy consumption of network interfaces in hand-held devices. *IEICE Trans. On Communication*, E80-B(8):1125–1131.

[106] Suri, V. and Gupta, H. M. (2006). An energy efficiency-based performance comparison of dsr and aodv. *IETE Journal of Research*, 52(4):315–324.

[107] Tilak, S., Abu-Ghazaleh, N. B., and Heinzelman, W. (2002). A taxonomy of wireless micro-sensor network models. *SIGMOBILE Mob. Comput. Commun. Rev.*, 6(2):28–36.

[108] Wang, W., Xie, F., and Chatterjee, M. (2007). An integrated study on mobility models and scalable routing protocols in vanets. In *2007 Mobile Networking for Vehicular Environments*, pages 97–102.

[109] Wieselthier, J., Nguyen, G., and Ephremides, A. (2002). Energy-efficient broadcast and multicast trees in wireless networks. *Mobile Networks and Applications*, 7(6):481–492.

[110] Woo, A., Tong, T., and Culler, D. (2003). Taming the underlying challenges of reliable multihop routing in sensor networks. In *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, SenSys '03, pages 14–27, New York, NY, USA. ACM.

[111] Xu, Y., Heidemann, J., and Estrin, D. (2001). Geography-informed energy conservation for ad hoc routing. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, MobiCom '01, pages 70–84, New York, NY, USA. ACM.

[112] Yao, Y. and Gehrke, J. (2002). The cougar approach to in-network query processing in sensor networks. *SIGMOD Rec.*, 31(3):9–18.

[113] Yerra, R. and Rajalakshmi, P. (2013). Effect of relay nodes on end-to-end delay in multi-hop wireless ad-hoc networks. In *Advanced Information Networking and Applications Workshops (WAINA), 2013 27th International Conference on*, pages 343–348.

[114] Yu, F., Li, Y., Fang, F., and Chen, Q. (2007). A new tora-based energy aware routing protocol in mobile ad hoc networks. In *Internet, 2007. ICI 2007. 3rd IEEE/IFIP International Conference in Central Asia on*, pages 1–4.

[115] Yu, Y., Govindan, R., and Estrin, D. (2001). Geographical and energy aware routing: a recursive data dissemination protocol for wireless sensor networks. Technical report.

[116] Zeng, K., Lou, W., Yang, J., and Brown, III, D. R. (2007). On throughput efficiency of geographic opportunistic routing in multihop wireless networks. *Mob. Netw. Appl.*, 12(5):347–357.

[117] Zeng, K., Yang, Z., and Lou, W. (2010). Opportunistic routing in multi-radio multi-channel multi-hop wireless networks. *Wireless Communications, IEEE Transactions on*, 9(11):3512–3521.

[118] Zhang, H. and Shen, H. (2010). Energy-efficient beaconless geographic routing in wireless sensor networks. *Parallel and Distributed Systems, IEEE Transactions on*, 21(6):881–896.

[119] Zhong, Z. and Nelakuditi, S. (2007). On the efficacy of opportunistic routing. In *Sensor, Mesh and Ad Hoc Communications and Networks, 2007. SECON '07. 4th Annual IEEE Communications Society Conference on*, pages 441–450.

[120] Zhou, Z., Peng, Z., Cui, J.-H., and Shi, Z. (2011). Efficient multipath communication for time-critical applications in underwater acoustic sensor networks. *Networking, IEEE/ACM Transactions on*, 19(1):28–41.

[121] Zhou, Z., Zhou, S., Cui, S., and Cui, J.-H. (2006). Energy-efficient cooperative communication in clustered wireless sensor networks. In *Military Communications Conference, 2006. MILCOM 2006. IEEE*, pages 1–7.

[122] Zorzi, M. and Rao, R. (2003). Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance. *Mobile Computing, IEEE Transactions on*, 2(4):337–348.

[123] Zubow, A., Kurth, M., and Redlich, J.-P. (2008). Opportunistic protocols in multi-rate environments. In *Sensor Technologies and Applications, 2008. SENSORCOMM '08. Second International Conference on*, pages 743–751.