Cross layer design for hierarchical routing protocol for wireless ad hoc network

Mohammed Tarique
University of Windsor

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Cross Layer Design for Hierarchical Routing
Protocol for Wireless Ad Hoc Network

by

Mohammed Tarique

A Dissertation
Submitted to the Faculty of Graduate Studies
through the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada
2007
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Abstract

Mobile Ad hoc Networks (MANETs) are becoming popular as a means of providing temporary communication facility among a group of people because MANETs can be set-up and deployed without any infrastructure. MANETs are self-configuring and self-organizing. Routing protocol is the most important element of MANET. Routing protocols for MANET can be broadly classified as proactive routing protocol and reactive routing protocol. In proactive routing protocols like Destination Sequence Distance Vector (DSDV), mobile nodes periodically exchange routing information among themselves. Hence proactive routing protocols generate high overhead messages in the network. On the other hand, reactive routing protocols like Ad hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR) work on-demand. Hence reactive routing protocols generate less number of overhead messages in the network compared to proactive routing protocols. But reactive routing protocols use a global search mechanism called 'flooding' during the route discovery process. By 'flooding' mechanism a source node can discover multiple routes to a destination. 'Flooding' generates a huge number of overhead messages in the network. That huge overhead messages affect the performance of reactive routing protocols in term of network throughput. That kind of performance problem is called 'scaling' problem. Hierarchical Dynamic Source Routing (HDSR) protocol has been proposed to solve that scaling problem. The DSR protocol has been modified to implement HDSR protocol. HDSR protocol reduces 'flooding' problem of reactive routing protocols by introducing hierarchy among
ABSTRACT

nodes. In HDSR protocol, 'flooding' effect is minimized by restricting nodes that should participate in route discovery process based on their status in the network. It is shown that HDSR protocol reduces overhead messages by 80% and reduces end-to-end delay per packet by 70% compared to regular DSR protocol. Hence the network throughput is also increased by 50%. To further improve the performance of HDSR protocol, less congested nodes are selected in route discovery process. In order to do that HDSR protocol is modified to implement a cross layer based routing protocol. It is shown that kind of cross layer based HDSR protocol further reduces delays of HDSR protocol by 20%.

HDSR protocol has been made energy aware by combining it with an energy aware protocol called Minimum Energy Dynamic Source Routing (MEDSR) protocol. The resultant protocol is called Hierarchical Minimum Energy Dynamic Source Routing (HMEEDSR) protocol. It is shown via simulations that HMEEDSR not only reduces overhead but it also delivers 1.5 times more packets to the destination compared to DSR protocol.

HDSR protocol has an unfair load distribution problem. Because when a mobile node decides to participate in the route discovery process, that mobile node continues forwarding packet from different sources and may be congested eventually. HDSR protocol has been modified to implement Cross-layer based Multi-path Hierarchical Dynamic Source Routing (CMHDSR) protocol. In CMHDSR protocol network traffic is evenly distributed among a set of nodes. Simulations studies show CMHDSR protocol further reduces end-to-end delay of HDSR protocol by 10%.
To my son Ayman Sabih, wife Rumana Islam and my parents.
Acknowledgement

The research work that has been framed into this thesis has been thoroughly enjoyable. That enjoyment is largely a result of the interaction that I have had with my supervisor, committee members and colleagues. I feel very privileged to have worked with my supervisor, Kemal E. Tepe. I feel very proud of becoming the first PHD student of my supervisor. I would like to thank him for giving me an opportunity to explore a very new field of research area. We spent long hours together in writing our papers. It is remarkable that we have worked together for as long as 18 hours a day. I am grateful to him for his moral support during my difficult days of my student life. I am very grateful to my committee members Shervin Erfani, Mohammad Khalid and Ziad Kobti. To each of them I owe a great debt of gratitude for their patience, inspiration and participation in this work. I would also like to thank Majid Ahmadi for giving me an opportunity to become a proud student of this university. I would also like to thank Sid Ahmed for always asking me to graduate as soon as possible. I spent many enjoyable hours with department members and fellow students chatting about my latest crazy ideas over a cup of coffee. Without this rich environment I doubt that many of my ideas would have come to fruition. Ontario Ministry of Colleges and Universities, and Kemal E. Tepe were very generous in providing me with scholarship and research assistance. Thanks also to my wonderful wife, Rumana Islam, who has been extremely understanding and supportive during my studies. I feel very lucky to have a wife who shares my enthusiasm for academic pursuits.
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<td>Ad hoc On-demand Distance Vector</td>
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<td>Address Resolution Protocol</td>
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<td>BER</td>
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<td>CBR</td>
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<td>CPU</td>
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<td>CMMBR</td>
<td>Conditional Max-Min Battery capacity Routing</td>
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<td>DSDV</td>
<td>Destination Sequence Distance Vector</td>
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<td>DARPA</td>
<td>Defense Adavance Research Project Agency</td>
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<td>DHCP</td>
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<td>Distributed Coordination Function</td>
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<td>FTP</td>
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<td>GPS</td>
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<td>PBOA</td>
<td>Progressive Back Off Algorithm</td>
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<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
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<td>RTS</td>
<td>Request To Send</td>
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<td>RR</td>
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<td>RAR</td>
<td>Retransmission Aware Routing</td>
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<td>SIFS</td>
<td>Short Inter Frame Space</td>
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<tr>
<td>TCP</td>
<td>Transport Control Protocol</td>
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<tr>
<td>UDP</td>
<td>Unigram Data Protocol</td>
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<td>VINT</td>
<td>Virtual InterNetwork Testbed</td>
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Chapter 1

Introduction

1.1 Motivation

Wireless networking has been an active research focus since the early days of packet radio network introduced by Defense Advanced Research Project Agency (DARPA) [33]. Recent developments in wireless devices and applications have attracted a large number of researchers both in academia and industries. Those devices such as laptop computers, personal digital assistant (PDA), pagers and cellular telephones have become portable now. Users can carry those devices to any place at any time. Hence there is a need for a network that can be readily deployed at any place at any time without any centralized administration. In some cases infrastructure based network is hard to build in a scenario like battlefield. A typical operation of such network is shown in Figure 1.1. In that scenario, an infrastructure based network cannot support the communication among soldiers, war ships, fighter planes, tanks and other combat equipment, because those constituents of the network are moving in different directions and also in unpredictable ways. In some cases there may not be any existing infrastructure to build a network. Infrastructure may be destroyed by natural calamity such as cyclone, tsunami and tornado. Hence there is always a need to set up a temporary network among a group of users without any pre-existing infrastruc-
ture. Mobile Ad hoc Network (MANET) is considered a suitable solution for that kind of temporary network. MANET consists of a group of mobile nodes, which have limited battery capacity and also limited processing power. MANET is self-organizing and self-configuring. Some of the other applications of MANET include sensor network, personal area network and distributed control system [24]. Those applications impose diversified design and performance constraints on MANET.

Figure 1.1: Example of Mobile Ad hoc Network (MANET)

MANET has many unique characteristics, which are not present in wired network. It has dynamic topology. Mobile nodes can join and leave the network at any time. Hence route 'breakage' is a very frequent phenomenon in MANET. The medium of communication in MANET is wireless, which has high packet loss, inherent unreliability, high interference and noise. Since wireless medium is shared among a group of mobile nodes, MANET has limited bandwidth. Mobile nodes communicate with each other in a multi-hop fashion because they have limited transmission range.

Routing protocol is the most important element of MANET because it provides to MANET self-organizing and self-configuring capabilities. Researchers have proposed a num-
ber of routing protocols for MANET. Those routing protocols can be broadly classified as proactive and reactive. In proactive routing protocols like Destination Sequence Distance Vector (DSDV) [53], mobile nodes periodically exchange routing information among themselves. That kind of periodic routing information exchange among nodes generates a huge number of overhead packets in the network. That is why proactive routing protocols are not considered suitable for MANET. Reactive routing protocols like Ad hoc On-demand Distance Vector (AODV) [54] and Dynamic Source Routing (DSR) [10] work on-demand. That means a route is discovered when it is required. Hence a huge number of overhead packets can be reduced in reactive routing protocols compared to proactive routing protocols. But reactive routing protocols use a global search procedure called 'flooding' to discover routes. By using 'flooding', a mobile node generates a special type of packet called Route Request (RR) packet and broadcasts that packet to its neighbors. The neighbors of that node add their addresses in that RR packet and re-broadcast that packet to their neighbors. This process goes on until the RR packet is received by the destination. Thus the whole network becomes 'flooded' with the RR packets. That kind of 'flooding' does not affect the performance of a small network. But as the network size gets larger, 'flooding' can affect the performance of a network significantly. Some of the problems related to 'flooding' are: (1) collision, (2) contention, and (3) redundancy [52]. When an RR packet is received by all neighbors of a transmitting node, all of those neighbors try to re-broadcast that RR packet at the same time. Those simultaneous re-broadcasted RR packets can cause collisions. Since all neighbors try to re-broadcast at the same time, those neighbors will contend with each other to get access to the medium. There is also a chance that a node can receive multiple copies of the same RR packet from its neighbors. Those RR packets do not contain any new useful information. Thus 'flooding' generates a huge number of redundant packets in the network. There have been proposals for 'flooding' minimization. Those proposals are based on the principle that some selected nodes will re-broadcast RR packet and other nodes will drop it. Those proposals can be broadly classified as (1) location based scheme [44], (2) cluster based schemes [5, 7, 6, 16, 38, 46] and [69], and (3) probabilistic based schemes [26, 37, 61] and [73]. In location based schemes nodes partici-
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Mobile nodes participate in 'flooding' process based on their locations in the network. In cluster based scheme, a group of nodes come in close proximity and form a cluster. In a cluster there is a 'cluster head' and a number of 'ordinary nodes'. If an ordinary node is within the transmission ranges of two 'cluster heads', that node is called 'gateway'. In a probabilistic scheme a mobile node broadcasts a RR packet based on a probability, which is less than 1.0. The common problem of location based scheme, cluster based scheme and probabilistic scheme is that the global knowledge about the network should be available to each node. In order to provide that global knowledge in location based scheme, Global Positioning System (GPS) is suggested by researchers. But providing mobile node with GPS incurs additional hardware and software, and obviously extra cost. In cluster based scheme and probabilistic scheme, 'Hello' messages are used to collect global network information. By exchanging 'Hello' messages, mobile nodes can determine the relative location of each other. But that kind of 'Hello' messaging also incurs undesirable additional overhead in the network.

Congestion is another problem of MANET. Reactive routing protocol like DSR or AODV uses shortest hop algorithm for the routing decision. That means if a source node discovers multiple paths to a destination node, it chooses the path that has the shortest number of hops. It is shown in [55] that the shortest hop routing may not be a good choice for MANET. An analysis presented in [55] shows that nodes located around the center of the network carry more traffic compared to other nodes located around the perimeter of the network. Hence one section of a network is congested whereas the other section of the same network is less congested. Packets traveling along those congested areas experience longer delays. Using congestion information to improve routing efficiency in MANET has also been investigated by other researchers as well; some are [28] and [72]. In those studies, congestion information is obtained from queues of the network interfaces of the nodes and used in the routing decision to improve delay.

Energy constraint is another issue in MANET. Mobile node has limited battery capacity. One of the reasons of node failure is battery exhaustion. In some cases battery of a mobile node can not be replaced or recharged. Since mobile node usually communicates in multi-hop fashion, the failure of a single node can greatly affect the performance of the

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whole network. Hence the availability of each mobile node is equally important for the proper operation of the network. To ensure efficient use of battery capacity, researchers have proposed energy aware routing protocols. Those protocols use different approaches to save node energy. Those approaches can be broadly classified as: (1) transmit power control [8, 13, 18, 40, 50] and [63], (2) load distribution [70] and [80], and (3) sleep/power down [14] and [86]. In transmit power control approach, the transmit power of mobile node is controlled to maintain connected topology of the network. The main objective is to find the best route that minimizes the total energy consumption while transmitting packets between a source and a destination. In load distribution approach, network traffic is distributed among nodes to maximize the life-time of the network. In sleep/power-down approaches some nodes are put into sleep/power-down mode; whereas other nodes are put into active mode. Mobile nodes save energy when they are in sleep/power-down mode and dissipates energy when they are in active mode. Although different approaches have been used to save node energy, all energy aware routing protocols show that network life can be maximized if node energy is taken into consideration in the routing decision.

Unfair load distribution is another problem of reactive routing protocol. Once all paths have been discovered by using the 'flooding' techniques, the source node chooses a path, which is usually the shortest one. Studies in [4, 9, 55] and [74] show that the shortest path algorithm is not a good choice for MANET. When the shortest path algorithm is used, nodes located around the center of the network carry more traffic compared to those located at the perimeter of the network. When a number of connections are set up in the network, the wireless links lying around the center of the network carry more traffic and hence get congested, which affect the performance of the network in terms of delay and throughput. In mobility scenarios, the shortest path may break due to node movement. Moreover, communication through wireless medium is unreliable, and is also subjected to link errors, especially when MANET is deployed in a hostile environment. To overcome limitations of the shortest path routing protocols, researchers have suggested multipath routing instead. Multipath routing protocols proposed for MANET can be broadly classified as (a) delay-aware multipath routing protocols, (b) reliable multipath routing protocols, (c) minimum
overhead multipath routing protocols, (d) energy efficient multipath routing protocols and (e) hybrid multipath routing protocols. Delay-aware multipath routing protocols, proposed in [12, 29, 32, 43] and [45], choose multiple paths so that overall delay performance of a network is improved. Reliable multipath routing protocols, proposed in [11, 41, 47, 74, 75, 77, 81] and [84] support reliable data transfer between source and destination. Minimum overhead multipath routing protocols, proposed in [3, 39, 49, 51, 79, 85] and [88], discover and use multiple paths by using minimum overhead control messages. Energy efficient multipath routing protocols as proposed in [19] and [42], maximize the life-time of a network by using energy efficient path selection. Hybrid multipath routing protocols proposed in [76] and [78], use both the shortest path and multipath algorithms in routing protocols. Those multipath routing protocols show that network performance in terms of delay and throughput can be improved significantly if fair load distribution can be ensured in the network.

Although an efficient routing protocol should reduce flooding effect, improve congestion and provide energy efficiency, a routing protocol may not meet all those requirements. For example, some energy aware routing protocols can maximize network life, but it can incur additional overhead packets in the network [50]. Hence there is always a trade off. On the other hand, MANET has its own performance objectives based on specific applications. Those applications have their own unique system level requirements. For example, reliability is the major issue in distributed control network. Network life-time and bandwidth allocation are also the major issues in personal area network. Since MANET needs to meet diversified application requirements, researchers suggested in [15, 24] and [58] that a fixed protocol stack like Open System Interface (OSI) model is not suitable for MANET. They suggest interactions among protocol layers are essential for MANET. That kind of interaction among protocol stacks is termed as "Cross Layer" design [24]. Some of the examples of cross layer design are [2, 24, 87] and [89]. A novel cross layer design concept that improve network throughput significantly by using interactions among physical layer, MAC layer and network layer has been proposed in [87]. Interaction between physical layer and MAC layer has been investigated in [2] to achieve automatic transmission rate adaptation. That
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rate adaptation mechanism improves spectrum efficiency while keeping packet delay minimized. The joint effect of MAC layer and physical layer on power efficiency was investigated in [89]. Authors present a study of the link adaptation for a power efficient transmission by selecting a proper transmission mode and power level. In [71], authors investigate to improve the performance of medium access scheme for MANET using cross layer design. They introduced Progressive Back Off Algorithm (PBOA) in [71] and showed that PBOA outperforms Carrier Sense Multiple Access mechanism with Collision Avoidance (CSMA/CA) if medium access control mechanism is combined with power control. Energy efficient scheme based on cross layer interaction is presented in [58]. Energy conservation is achieved based on network layer and MAC layer interactions. In [15] authors presented a distributed power control algorithm that couple with the TCP protocol to increase the end-to-end throughput and energy efficiency of multi-hop transmissions in MANET.

1.2 Contribution and applicability

This dissertation addresses the problem of efficient reactive routing protocol for MANET that reduces 'flooding' effects by introducing a hierarchy among network nodes. The proposed routing protocol is called Hierarchical Dynamic Source Routing (HDSR) protocol [68]. The Dynamic Source Routing (DSR) protocol has been modified and optimized to implement HDSR protocol. In HDSR protocol, network nodes have been classified into Mobile Node (MN) and Forwarding Node (FN). MN acts as source or destination. FN participates in the packet forwarding operation. Since only FN participates in the route discovery phase of the protocol, a huge number of overhead packets is eliminated in the network. There will be less contentions and collisions caused by overhead packets generated during the route discovery process. In a given area of MANET, less number of nodes will contend for the medium. Hence network resource like bandwidth is used more efficiently in HDSR protocol compared to DSR protocol. That means the shared wireless medium is available for transmitting data packet instead of transmitting overhead packets. After receiving request packet from a source node, a few number of neighboring nodes re-broadcast that request message. Hence the packet collision probability is reduced. There is an FN selection algorithm in
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HDSR protocol [66]. After receiving a route request packet, network nodes execute the FN selection algorithm and determine their roles as FN or MN. Hence HDSR protocol is an on-demand reactive routing protocol. Although HDSR protocol is developed by modifying DSR protocol, FN selection algorithm can be applied to any on-demand routing protocol like AODV protocol. To further improve delay, FN selection algorithm has been modified so that FNs are located in the less congested area of the network. A cross layer design has been adopted to collect congestion information [66] of mobile nodes. Although FN selection algorithm addresses network layer problem, MAC layer congestion information is used in FN selection algorithm. It is shown in this dissertation that using congestion information in FN selection algorithm further improves the network performance in terms of delay and throughput [64]. According to modified FN selection algorithm, MNs, which are located in the less congested area of the network, are more likely to become FNs compared to other nodes located in the more congested area of the network. Hence FN selection algorithm is applicable to any MAC layer protocol like IEEE 802.11 [17], where congestion information is available.

In order to provide energy efficiency, transmit power level of mobile nodes are controlled to save energy. The sole objective of transmit power control is to make a node available for transmitting packet as long as possible with the limited battery capacity. In this dissertation, it is shown that there are some unique advantages when energy is saved by controlling transmit power and at the same time routing overhead is reduced by utilizing a hierarchical routing protocol.

Since overhead in the network can be reduced significantly by using a hierarchical routing protocol like HDSR, mobile nodes can save energy from transmitting less number of overhead packet. Hence mobile nodes will be left with more energy to transmit useful data packet [65]. But most of the energy aware routing protocols suggested in [13, 18, 40] and [63] do not target to reduce overhead packets in the network. Even energy aware routing protocol proposed in [50] generates extra overhead in the network. In this dissertation, an energy aware routing protocol called Minimum Energy Dynamic Source Routing (MEDSR) protocol has been proposed. In MEDSR protocol, the transmit power levels of nodes are reduced...
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to a minimum level while maintaining network connectivity. The MEDSR protocol has been combined with the HDSR protocol to implement Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) protocol. The HMEDSR protocol conceive the advantages of energy saving of MEDSR protocol and overhead reduction of HDSR protocol. Interaction between physical layer and the network layer has been used to implement HMEDSR protocol.

To ensure fair load distribution among network nodes, FN selection algorithm has been further modified. According to HDSR protocol, once an MN becomes an FN, it continues forwarding request packet for the sources that are located within the transmission range of that FN. Hence that FN gets congested and becomes over utilized eventually. To avoid those limitations of over utilization and congestion, a load distribution algorithm has been adopted in FN selection algorithm. The main objective is to distribute network traffic among a set of FNs so that no FN will be over utilized or under utilized. When an FN is congested, some of the traffic load of that FN is distributed among other FNs. Interaction between MAC layer and network layer has been used to ensure fair load distribution among FNs.

At a glance, the HDSR protocol has the following unique advantages compared to other 'flood' minimizing protocols

- No additional hardware (i.e., GPS) is required.
- No additional control message like 'Hello' message is needed. Existing control messages such as RR packet has been used. Hence HDSR protocol is a passive routing protocol.
- It works on-demand. That means nodes exercise FN selection algorithm when there is a need to discover a route.
- The global information about network is not required. FN selection algorithm uses only information that is already available at the node locally at different layers of protocol stacks.
- Cross layer interactions are used to implement HDSR protocol
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- The HDSR protocol ensures fair load distribution among nodes in the network.
- The HDSR protocol uses node energy efficiently. Hence network life is maximized.

1.3 Thesis outline

This dissertation is composed of 7 chapters. Each chapter will contain an introductory section to give an overview of each chapter and a conclusion.

This chapter has already given a motivation and applicability of this dissertation. 'Flooding' problem of MANET, an overview of Hierarchical Dynamic Source Routing (HDSR) protocol, Hierarchical Minimum Energy Dynamic Source Routing (MEDSR) protocol and fair load distribution among nodes are introduced.

A brief background of Mobile Ad hoc Network (MANET) is provided in Chapter 2. The operations of proactive and reactive routing protocols are explained. The detailed operation of Dynamic Source Routing (DSR) protocol and 'flooding' problems is explained in details in Chapter 2. The summary of related works about 'flooding' solutions is presented. Cross layer design for MANET is defined and some examples of cross layer design are mentioned to better explain the concept. Network Simulator (NS-2) has been used in this dissertation to simulate the protocols and performances of those protocols. Chapter 2 also contains background of NS-2. Performance analysis of DSR protocol that was the base protocol for comparison, will be presented in Chapter 2 as well.

Hierarchical Dynamic Source Routing (HDSR) protocol is introduced in Chapter 3. The advantages and disadvantages of HDSR protocol are explained in detail. FN selection algorithm is introduced in this chapter. A comparative performance analysis of DSR protocol and HDSR protocol is presented in this chapter. It is shown how cross layer design can be used to enhance the performance of HDSR protocol.

Energy Saving Dynamic Source Routing (ESDSR) protocol is described in Chapter 4. The routing algorithm of DSR protocol is modified to implement ESDSR protocol. It is shown that a network life can be maximized if routing protocol is made energy aware.

Minimum Energy Dynamic Source Routing (MEDSR) and Hierarchical Minimum En-
ergy Dynamic Source Routing (HMEDSR) protocols are introduced in Chapter 5. It is shown how energy can be saved by MEDSR protocol while maintaining connectivity of the network and also the advantages of energy saving routing protocol are shown when it is combined with HDSR protocol.

The need for fair load distribution among network nodes is explained in Chapter 6. How fair load distribution can be ensured in HDSR protocol and how fair load distribution can enhance the performance of HDSR protocol is also shown in that chapter.

Chapter 7 provides a summary of this work. Some future research directions are proposed.
Chapter 2

Background

2.1 Introduction to Mobile Ad hoc Network (MANET)

Mobile Ad hoc Network (MANET) is a temporary network formed by a group of mobile nodes without the aid of any centralized administration. MANET is self-organizing and self-configuring. Setting up a MANET does not require any infrastructure. That is why MANET is considered a viable option of networking where there is no infrastructure present or where it is not possible to build an infrastructure-based network. Dynamic topology is an inherent characteristic of MANET. Mobile nodes are free to move at any time in any direction. Hence network topology may dynamically change in an unpredictable manner. That kind of topological changes result in high route breakages in the network. Since information is forwarded in peer-to-peer mode using multi-hop routing, maintaining routes under dynamic topology imposes significant challenges for the researchers in MANET. Initially MANET was developed to provide networking support in the military applications, where infrastructure based network is almost impossible to set up and maintain. Some of the other applications of MANET are in crisis management, telemedicine, tele-geoprocessing, process control, personal communication, virtual navigation, education and security.
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- **Crisis management:** When infrastructure based network of a given region is destroyed by natural disaster like tsunami, cyclone or tornado, MANET can be a viable solution to restore communication in that region within short period of time. On the other hand, setting up of a wired network in that region might take several days or several weeks.

- **Telemedicine:** MANET can assist a paramedic to access the medical record of a victim from a remote crash site. Paramedic may need to send victim's X-rays and other diagnostic records to a remote medical center for further medicare support. Paramedic may also need to set up a video conferencing with a surgeon from a remote crash site.

- **Tele-geoprocessing:** MANET can be employed to monitor some unusual environmental changes. Tsunami monitoring system is an example of that kind of application. By integrating Geographical Information System (GIS) and Global Positioning System (GPS) with high capacity MANET enables that kind of tele-geoprocessing system.

- **Process control:** MANET can be employed to monitor an industrial process. Temperature, pressure, humidity and other process parameters can be monitored remotely by using MANET.

- **Personal communication:** Personal laptop, personal digital assistant (PDA), television, stereo, and other devices can form MANET for multimedia communication.

- **Virtual navigation:** MANET can be employed to build a virtual navigation system that can help rescue workers to plan a rescue operation. The graphical representation of streets, buildings and physical characteristics of large metropolis can be stored into a data base. That database can help the rescue worker to navigate through the streets and buildings of that metropolis.

- **Education via Internet:** Educational opportunities can be made available to the student who are located in a remote area and who are unable to attend the school because of distance.
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- Security: In order to monitor an area sensors can be deployed. Those sensors can form a MANET to communicate among themselves and to the control center.

2.2 Routing protocols of MANET

Designing efficient routing protocol has been the main focus of the researches in MANET for last several years. Many routing protocols have been suggested for MANET. Those routing protocols are being reviewed by the Internet Engineering Task Force (IETF)'s MANET working group for standardization [31]. The responsibilities of a routing protocol include exchanging the routing information among nodes, finding feasible paths to a destination, minimizing consumption of node's energy, maintaining the discovered routes, and utilizing bandwidth efficiently. Designing an efficient routing protocol for MANET is a challenging task. The major challenges are originated from the inherent peculiar characteristics of MANET such as mobility, bandwidth constraint, error prone shared medium, congestion and other resource constraint.

- Mobility: One of the most important properties of MANET is the mobility associated with the node. The mobility of nodes results in frequent route breakages, packet collisions, transient loops, stale routing information, and difficulty in resource reservation. An efficient routing protocol should be able to address all these issues related to node mobility.

- Bandwidth constraint: Since the wireless channel is shared by a number of mobile nodes in a given region, the bandwidth available per node depends on the number of nodes located in a given region and the traffic patterns of those mobile nodes. Thus only a fraction of the total bandwidth will be available for each node.

- Error prone and shared channel: High bit error rate (BER) is an inherent characteristic of wireless network. Routing protocols designed for MANET should consider BER while making routing decision. The state of the wireless link such as signal to noise ratio and path loss should be considered while designing an efficient routing protocol for MANET.
• Location dependent contention: The load on the wireless channel varies with the number of nodes present in given region. Contention for the channel becomes high when the number of nodes increases for a given region. The high contention for channel causes high number of collisions and a subsequent wastage of bandwidth. A good routing protocol should avoid forming high contention region in the network.

• Other resource constraints: The constraints on node resources such as computing power, battery power, and buffer storage also need to be considered while designing an efficient routing protocol.

A good routing protocol for MANET should have minimum route acquisition time, quick route reconfiguration, loop free route discovery, minimal control overhead and scalable. Those properties can be defined as follows:

• Minimum route acquisition time: Route acquisition time of a routing protocol may vary with the size of the network, collision probability and packet loss probability of the control messages that are used during route discovery process. A source node should have minimum route acquisition time to a destination.

• Quick route reconfiguration: The topology of MANET usually goes through an unpredictable changes. Hence route breakage is a normal phenomenon in MANET. Routing protocol should handle path breakage as quickly as possible. It should find alternative paths as soon as a route breakage occurs.

• Loop-free routing: To ensure loop free routing is a fundamental requirement of any routing protocol. Due to random movement of nodes, there are chances to discover transient loops. A routing protocol should detect such transient routing loops and take corrective actions accordingly.

• Minimum control overhead: High control overhead is generated while discovering route as well as maintaining those routes. That control overhead packets should be kept as minimal as possible. The control packets consume precious bandwidth and can cause collisions with data packets, and thereby can reduce network throughput.
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- Scalability: Scalability is the ability of the routing protocol to scale well with the network size. To ensure scalability, minimization of control overhead and adaptation of the routing protocol with the network size are required.

2.3 Review of routing protocols for MANET

Many routing protocols have been suggested for MANET. Those routing protocols can be classified either as proactive or reactive. Proactive protocols attempt to continuously evaluate the routes within the network. In proactive routing protocol, up-to-date routing information is available at each node. When a route is needed, there is negligible delay in determining that route. In proactive routing protocol, mobile nodes periodically exchange routing information among themselves to maintain up-to-date record of routing. But that kind of periodic exchanging of routing information among nodes generates a huge number of overhead packets in the network. This is the reason why proactive routing protocols are not considered suitable for MANET. On the other hand reactive protocols invoke routing decision only when it is needed. When a route is needed, some kind of global search procedure called 'flooding' or 'blind flooding' is initiated to discover a route to a destination. In reactive protocols the delay to determine a route can be significant because routing information may not be available at the time when a mobile node needs to communicate with the destination node. Furthermore, 'flooding' technique incurs significant control overhead in the network. Because of this delay and excessive control overhead, pure reactive routing protocol may not be adequate for any real time communication. In the following section, we will explain briefly some of those proactive and reactive protocols to understand their operations.

2.4 Proactive routing protocols

In proactive routing protocols each node maintains one or more routing tables. That is why proactive routing protocols are often called table driven protocols. Those tables contain routing information that is always consistent and up to date. Proactive routing protocols
respond to changes in network topology. By propagating the information of topology change throughout the network, each node maintains a consistent view of the current network condition. Some of the existing proactive routing protocols are Destination Sequence Distance Vector (DSDV) [53] and Cluster head Gateway Switch Routing (CGSR) [46]. The DSDV routing protocol is a proactive routing protocol based on the classic Bellman-Ford routing algorithm [9]. Each mobile node maintains a routing table that contains information about a route to every possible destination in the network and the number of hops of each route. Each route contains a sequence number assigned by the destination node. That sequence number allows a mobile node to distinguish between stale routes and new routes. Routing tables are periodically broadcasted in the network so that routing information maintained by nodes are consistent. But the amount of overhead packets generated by these updates can be large. To reduce the number of overhead packet, the updates are done by using two types of packets called 'full dump' packets and 'incremental' packets. The 'full dump' packet carries all the available routing information. When there is only occasional movement, 'full dump' packet are used to update routing information. On the other hand, if there is any movement in the network after the exchange of 'full dump' packet, smaller 'incremental' packets are used. The 'incremental' packets are smaller in size compared to 'full dump' packet and hence occupy the channel for a short period of time. The information contained in the 'incremental' packets is maintained by a node in a separate table. The Cluster head Gateway Switch Routing (CGSR) [46] protocol was proposed to further reduce the overhead of DSDV protocol. The CGSR protocol is different from the DSDV protocol in terms of addressing and network organization. Instead of flat network, CGSR protocol classifies network nodes into 'Cluster Head(CH)', 'Ordinary node' and 'Gateway'. The Cluster Heads (CHs) control a group of mobile nodes and hence achieve a hierarchical framework. The CGSR uses a complex distributed algorithm to identify 'Cluster Head'. 'Gateway' nodes are those that are within communication ranges of two or more CHs. When a node has some packet to send to a destination, it sends that packet to its CH. From there it is routed to the 'Gateway', then to another CH and so on till the packet reaches to the CH of the destination node. The destination CH sends that packet to the destination node. Each node
maintains a cluster member table, which stores the destination CH for every node in the network. CGSR routing protocol uses broadcast packet to exchange cluster member table periodically. In addition to the cluster member table, each node also maintains a routing table, which is used to determine the next hop to reach the destination. One major disadvantage of CGSR protocol is that frequent topology changes adversely affect performance of a network. Because nodes spend more time in selecting a CH rather relaying packets when there are frequent topology changes. The Least Cluster Change (LCC) algorithm has also been proposed in [46] to minimize CH changes.

2.5 Reactive routing protocols

Reactive routing protocol is also called source initiated on-demand routing protocol. When a source generates some packets to a destination and does not know any route; it initiates a route discovery process in the network. This process ends when all possible routes to the destination have been discovered. The discovered routes are maintained by a route maintenance procedure. If a discovered route breaks, route maintenance is executed by mobile nodes to notify the source about that route breakage. Ad hoc On-demand Distance Vector Routing (AODV) [54] routing protocol falls in this category. The AODV protocol is built over the DSDV [53] routing algorithm. In AODV protocol, the nodes that are not on a particular path neither do maintain routing information, nor do they participate in the routing information exchanging. Hence AODV has less overhead compared to DSDV. During the route discovery process, a source initiates the route discovery by broadcasting a Route Request (RREQ) packet to all of its neighbors. Those neighbors forward that RREQ packets to their neighbors, and so on until either the destination or an intermediate node that has fresh route to the destination replies back. AODV protocol uses destination sequence number to ensure that all routes are loop free and contain the most recent route information. Each node maintains a unique sequence number and a broadcast ID, which is incremented each time when a node initiates a route discovery. The broadcast ID and the node's IP address, uniquely identifies each RREQ used in the route discovery. In the RREQ message, the initiator node includes the following information: (a) its own sequence number,
(b) the broadcast id, and (c) the most recent sequence number. When an intermediate node receives that RREQ message, it replies only if it has a route to the destination with a sequence number greater than or at least equal to that contained in the RREQ. During the process of forwarding the RREQ, intermediate nodes establish a reverse path by recording the address of the neighbor from which the first copy of the broadcast packet was received in the routing table. If an intermediate node receives additional copies of the same RREQ, it discards that packet. Once the RREQ reaches the destination or an intermediate node with a fresh enough route, that destination/intermediate node responds by unicasting a route reply (RREP) packet back to the neighbor from which it first received the RREQ. As the RREP is routed back along the reverse path, nodes along that path set up forward route entries in their routing tables. That forward route entry points to the node from which RREP came from. Each route entry has an associated route timer. When that route timer expires, the associated route entry is deleted.

In AODV protocol, discovered routes are maintained by a route maintenance mechanism. According to that route maintenance, if a node along the route moves away and causes route breakage, its upstream neighboring node detects that the link breakage and propagates a route breakage notification message to each of its upstream neighbors. Those nodes in turn propagate that route breakage notification message to their upstream neighbors, and so on until the source node is reached. The source node re-initiates a route discovery for that destination. AODV protocol uses 'Hello' messages. Those 'Hello' messages are periodically broadcasted among neighboring nodes to maintain the local connectivity.

2.6 Dynamic Source Routing (DSR) protocol

The Dynamic Source Routing (DSR) protocol is another reactive routing protocol. The routing protocols proposed in this dissertation are modifications of DSR protocol. That is why DSR protocol is explained, investigated and analyzed in details in this section. The DSR protocol consists of two main mechanisms: (1) route discovery, and (2) route maintenance. By route discovery, a source discovers routes to the destination. By route maintenance a source node can detect topology changes of the network. Route discovery
and route maintenance of DSR protocol have been designed based on the following basic assumptions.

- All mobile nodes of MANET are willing to participate in network operation.
- The distance between two nodes located at the two extreme corners of the MANET is 15 hops, but may often be greater than 1.
- A mobile node can detect corrupted packet and discard that packet. But that kind of corrupted packet handling is beyond the scope of DSR protocol.
- Mobile node may move at any time in any direction without notice, but the speed with which mobile node moves is moderate with respect to transmission latency and wireless transmission range of the underlying hardware.
- Network card of mobile node can operate in 'promiscuous receive' mode. This mode causes the hardware to deliver every received packet to the network driver software without filtering based on link-layer destination address.
- Wireless link between two mobile node works bidirectionally provided underlying Medium Access Control (MAC) layer uses mechanism like four way handshaking. The four way hand shaking involves exchanges of Request to Send (RTS), Clear to Send (CTS), Data and Acknowledgment(ACK) packets between a transmitting and receiving mobile nodes.
- The IP address used by a node using the DSR protocol may be assigned by any mechanism such as static assignment or use of DHCP for dynamic assignment.

2.6.1 Route discovery

Route discovery is the mechanism by which a source node finds a route to the destination. During that mechanism if a node, called source, wants to send some packets to another node, called destination, first searches its route cache to find a route. If it cannot find a route in the cache, it will initiate a route discovery mechanism to find a route to the
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destination. To initiate the route discovery, source node transmits a route request message as a local broadcast packet, which is received by other nodes that are currently within wireless transmission range. Each route request contains addresses of source and destination nodes, and a unique identification number called request identification (ID). Each node that receives the request checks if it is the destination, if it is not, it appends its address, which will indicate the route that the packet has followed. Then the node re-broadcasts the request messages. But if it is the destination, then it sends a route reply to the source node after copying the accumulated routing information in the route request packet to route reply packets. When the source node receives the route reply packet, it records new route in its cache and send packets using the route. Intermediate nodes that receive route request messages more than once ignore the request. Source and destination addresses and unique request ID help nodes to identify duplicate requests.

![Route discovery of DSR protocol](image)

**Figure 2.1: Route discovery of DSR protocol**

A typical route discovery mechanism of DSR protocol is shown in Figure 2.1. The source $S$ initiates a route discovery to discover routes to the destination $D$. When a neighboring node $A$ and $E$ receive that request message, those nodes add their addresses in the request packet and forward that request packet to their neighbors. This process goes on until that request packet is received by the destination node $D$. When $D$ receives that request message, it creates a reply packet and sends that reply packet to the source. The reply packet contains
the route that has just been discovered. Let us assume, in the scenario of Figure 2.1, the source has discovered two paths \( S - A - B - C - D \) and \( S - E - F - G - H - I - D \). Hence the destination node will send two route reply packets to the source, which is shown in Figure 2.2. One reply packet contains the route \( S - A - B - C - D \) and the other route reply packet contains the route \( S - E - F - G - H - I - D \). After discovering those paths, the source should select the shortest hop path \( S - A - B - C - D \) for transmitting data packet.

2.6.2 Route maintenance

Route maintenance is a mechanism by which a node is able to detect changes in the network topology. For example, if a node on the route cannot send a packet because of broken link, then it initiates the route maintenance mechanism. According to that mechanism, a node sends messages to the source and other nodes that are on this route. Acknowledgments provide confirmation about the links health. Those acknowledgments can be requested or they can be obtained passively using inherent messaging existed in medium access (MAC) protocols. For example, IEEE 802.11 Wireless LAN medium access layer provides acknowledgment for each packet. If the transmitting node does not receive any acknowledgment after sending a packet several times, it treats that link is broken, and marks all the routes
in the route cache that contains this link as 'invalid'. Also the node that discovers the broken link, sends route maintenance packets called route error message to other nodes. Nodes that receive those packets update their own route caches. If the source node receives route error message, it tries to find another route from its route cache. If it cannot find any other alternative route in the cache, it will initiate another route discovery mechanism for that destination. Route maintenance of DSR protocol is illustrated in Figure 2.3. Let

![Figure 2.3: Route maintenance of DSR protocol](image)

assume node C exhausts battery. Node B sends packet to C several times, but node C does not send any acknowledgment. Then node B assumes that the link B — C is broken and creates a route error message, and sends it to the source S. After receiving that route error message, the source marks the route S — A — B — C — D as invalid route in the route cache and uses alternative route (i.e., S — E — F — G — H — I — D).

### 2.7 Flooding problems of DSR protocol

In DSR, a node can learn and cache multiple routes to a destination by means of a single route discovery. Having multiple routes in the route cache allows quick reactions to the topology changes of the network. If one of the route fails, a source can use alternative route. The source does not need to initiate a new route discovery. To ensure this multiple
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Routing strategy work, all neighboring nodes are obligated to re-broadcast when they receive a route request. The ultimate outcome of this re-broadcasting is 'flooding' or 'storming' of overhead packets. Although some measures have been adopted in DSR protocol to reduce flooding such as limiting the rate of route discovery by using random back-off algorithm, imposing shorter hop count ('ring zero search' mechanism); flooding problem is still severe in DSR when the network size is large.

Some of the drawbacks related to flooding are:

- Redundant re-broadcast: When a mobile node decides to re-broadcast a route request message to its neighbors, all those neighbors may already have received that message from other nodes.

- Contention: After receiving route request message if all neighbors of a node decide to re-broadcast at the same time, those neighbors may severely contend with each other to get access to the medium.

- Collision: Collisions are more likely to occur when all neighboring nodes try to re-broadcast at the same time.

Figure 2.4: Redundant broadcast scenario 1

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2.7.1 Analysis of redundant broadcast

Redundancy of route request broadcasting is illustrated in Figure 2.4. In that scenario, node A is the source and node D is the destination. When A initiates the route discovery by broadcasting a request message, all other nodes re-broadcast that request message. Hence there will be total six broadcasts in the network if no attempt is made to reduce redundancy. On the other hand, if some nodes are selected among the network nodes that should broadcast request message and other nodes should not, the number of route request packet can be reduced. For example, let us assume that only node G is selected to forward that request messages and other nodes B, C, E and F are restricted to re-broadcast. The route discovery process under the modified condition is shown in Figure 2.5. It is shown in that figure that for the same route discovery initiated by A, there are only two broadcasts instead of six broadcasts. Hence four re-broadcasts can be reduced. But the number of paths discovered in this case is only one. Thus there is a trade off between the number of paths discovered and the number of overhead generated in the network.

The additional area covered by a new broadcast depends on the locations of the nodes. To demonstrate how additional area can be covered by each broadcast, let us consider an
2. BACKGROUND

Example depicted in Figure 2.6. In that scenario mobile node A sends a broadcast message and mobile node B decides to re-broadcast that message. Let us assume $r$ is the transmission range of A and B. The two hosts are separated by the distance $d$. The overlapping area covered by two broadcasts has been formulated in [73], which is given by

$$INC(d) = 4 \int_{d/2}^{r} \sqrt{r^2 - x^2} dx$$  \hspace{1cm} (2.1)

When $d = r$, the covered area is the largest, which is given by $\pi r^2 - INC(r) = 0.61\pi r^2$. This shows that a re-broadcast can provide a maximum 61% additional coverage over that already covered by the previous broadcast. When the distance between A and B is zero, the additional area coverage by the re-broadcast of node B is zero. Hence the additional area coverage by a re-broadcast depends on the distance between the transmitting node and the receiving node.

2.7.2 Analysis of contention

To understand the effect of contention, let us assume that mobile node A transmits a broadcast message and there are $n$ neighboring mobile nodes hear that message. If all those neighboring nodes try to re-broadcast that message, those nodes will contend each other to get access to the medium. An analysis shown in [52] that the contention is expected to be higher as the number of neighbors increases. It is also shown in [52] that the contention level depends on node density in the network.
2.7.3 Analysis of collision

Collision in MANET has been minimized by using IEEE 802.11 MAC layer, which uses a medium access control mechanism called Carrier Sense Multiple Access control with Collision Avoidance (CSMA/CA). The CSMA/CA requires that a mobile node should start a back-off procedure right after the mobile node transmitted a message, or when a mobile node wants to transmit but the medium is busy and the previous back-off has been done. But there are several cases that can not prevent packet collisions. Let us assume that medium surrounding a mobile node \(A\) has been free for a long time. When the neighboring nodes of \(A\) discover that the medium is free and try to re-broadcast, node \(A\) may also try to re-broadcast at the same time. The collision probability for IEEE 802.11 MAC layer has been formulated in \([4]\), which is given by

\[
\gamma = 1 - e^{-\left(\frac{n-1}{\beta}\right)^3}
\]  

(2.2)

where \(n\) is the number of neighbors in a given region, \(\beta\) is the parameter of the exponential back-off duration, thus \(\frac{1}{\beta}\) has units of time. From (2.2), it can be concluded that as the number of neighbors, \(n\), gets larger, the collision probability increases.

The problems related to flooding may not affect the performance of a network when the network size is small. In small network, there are few number of nodes present in a given region. But when the network gets larger, there will be more number of nodes in a given region. Hence there will be more redundancy, collision and contention, this is why flooding significantly affect the performance negatively in a network. In order to show the effects of flooding with performance, simulations results will be shown in the later section. Those simulations are done using a simulation tool called Network Simulator (NS-2) \([20]\). Next section will introduce this powerful simulation tool.

2.8 Network Simulator (NS-2)

Network Simulator (NS-2) is a discrete event simulator developed at University of California, Berkeley. NS-2 originated from Real Network Simulator \([30]\) at Cornell University, Ithica, New York in 1989. It has evolved substantially over the past few years supported by
Defense Advanced Research Project Agency (DARPA) through the Virtual Inter Network Testbed (VINT) project at Lawrence Berkeley National Laboratory (LBNL) in Berkeley, Xerox Palo Alto Research Center (PARC), University of California at Berkeley (UCB), and Information Science Institute (ISI) of University of Southern California (UCB). NS-2 includes substantial contributions from other researchers working at UCB, Monarch projects of Carnegie Mellon University (CMU) and Sun Microsystems. NS-2 provides researchers a tool to simulate and test the performances of network protocols. The simulator takes a network scenario as input, which consists of network topology, protocols, workload and control parameters. It produces performance results such as throughput, queuing delay and number of dropped packets. NS-2 can simulate Transport Control Protocol (TCP) and Unigram Data Protocol (UDP), traffic source behavior such as File Transfer Protocol (FTP), Telnet, Web, Constant Bit Rate (CBR), router queue management mechanism such as Drop Tail, routing algorithms such as Dynamic Source Routing (DSR), Ad hoc On-demand Distance Vector (AODV), Destination Sequence Distance Vector (DSDV) and MAC protocol like IEEE 802.11. NS-2 is a open source simulator and it is evolving continuously through research and development.

Currently, NS-2 is written in C++ and OTcl (Tcl script language with Object oriented extensions developed at MIT). Figure 2.7 shows a simplified model for NS-2. It has an Object oriented Tcl (OTcl) script consists of a simulation event scheduler and network component object libraries, and network setup libraries. Users program in OTcl script.
2. BACKGROUND

language, and setup and run a simulation network. The packet generated by the NS-2 has unique identification (id) and the record of each packet is stored in the trace file. Trace file stores all the events related to a packet such as when it was generated, what was the source node of that packet and when it reaches the destination. Network Animator (NAM) can show graphically the network activities in terms of packet drop, mobile node movement, energy levels and other network parameters.

2.9 Wireless network model

The Monarch project of Carnegie Mellon University extends the NS-2 to simulate wireless network. The extended NS-2 provided new elements at the physical, link and routing layer. Hence it is possible to construct and simulate wireless networks, LANs or multi-hop ad hoc networks. Figure 2.8 shows the logical overview of a wireless network proposed by Monarch project. Each mobile node is an independent unit and has its network interface connected to the common channel. Channel carries packets between mobile nodes. When a mobile node transmits a packet, that packet reaches to all the mobile nodes that have network interfaces connected to the common channel. While transmitting packet, mobile nodes use a predefined power level. The other mobile nodes receive that packet at a power level, which is determined by radio propagation model. In order to correctly receive a packet, a mobile node should receive a packet at a power level greater than a threshold value.

The mobile node architecture in NS-2 is shown in Figure 2.9. When a mobile node receives a packet over the channel, network interface records the interface properties of
the packet and invokes the propagation model. Based on the interface properties and propagation model, a mobile node's network interface determines whether that mobile node can receive the packet successfully or not. If a packet is successfully received by the network interface, it hands over the packet to the MAC layer. If the MAC layer determines that the packet was received error free and collision free, MAC layer hands over the packet to the node's entry point. If the receiving mobile node is the final destination of the packet, the address multiplexer will hand over the packet to the port demultiplexer and the port demultiplexer hands over the packet to the sink. On the other hand, if the receiving mobile node is not the final destination, the address multiplexer will hand over the packet to the default port. The routing agent determines the next hop address of that packet and sends that packet back to logical link layer. If the next hop address is an IP address, the LL quaries the Address Resolution Protocol (ARP) to convert IP address into a hardware
address. Once the hardware address is resolved, the packet is inserted into interface queue. The MAC layer takes the packet from the interface queue, accesses the medium and sends that packet to the network interface.

2.10 Performance analysis of DSR protocol

To investigate how many overhead packets are generated in the network and how those overhead packets can affect the performance of a network, DSR protocol was tested in a random network where 100 network nodes were uniformly distributed over an area of 1000m × 1000m. There were 5 pairs of connections in each simulation. Traffic sources were Constant Bit Rate (CBR) with 512 bytes per packet. Each CBR source generates packets at the rate of 1 packet per second. The source-destination pairs were placed randomly over the network but the number of pairs was constant during each simulation scenario. Each CBR started at random time and each simulation was run for 250 seconds. In order to increase the statistical reliability of the simulations, each scenario was simulated 10 times.

Figure 2.10: Overhead generated by DSR protocol
with different node topologies, which were constructed randomly. The reported results are
average of these 10 simulations. As underlying MAC protocol, IEEE 802.11 MAC layer
protocol in distributed coordination function (DCF) mode was used. All simulations were
carried out while the network nodes were static. The node density was kept constant when
the number of MNs in the network was increased. For example, if the area is $1000m \times 1000m$
when the number of MNs is 100, the area is $2000m \times 1000m$ when the number of MNs is
200. Overhead generated by the DSR protocol is shown in Figure 2.10. In that figure, the
overhead per packet was determined by the ratio of total number of overhead generated in
the network and the total number of packet delivered to the destination. It is shown that
0.24 overheads per packet were generated when the network size is 100 nodes. But that
overhead per packet increases to 0.6 and 1.01 when the network size increases to 200 nodes
and 300 nodes respectively. That means the overhead per packet increases by 1.5 times
and 4.2 times when network size was increased to 200 nodes and 300 nodes. The number
of overhead generated in the network also depends on how many route discovery processes
are initiated in the network. To investigate how overhead packet vary with the number
of connections, the number of connections was increased to 10 and 20 from 5. When 10
connections were set up in the network, the overhead per packet are 0.35, 0.7 and 1.15 for
network sizes of 100 nodes, 200 nodes and 300 nodes, respectively. When 20 connections
were set up in the network, the number of overhead per packet increases to 0.35, 0.73 and
1.56 for same network sizes. From the simulation results presented in Figure 2.10, it is
depicted that the overhead generated in the network depends on the network size as well
as on the number of connections set up in the network. The end-to-end delay performances
of those simulated networks are depicted in Figure 2.11. For the smallest network size of
100 nodes, the delay per packet is 0.016 second when there are 5 connections operating in
that network. But that delay increases to 0.03 second and 0.04 second for network size of
200 nodes and 300 nodes, respectively. That means delay per packet is increased by 50%
and 100% when network size is increased to 200 nodes and 300 nodes. That increase in
delay arises from the fact that packets are traveling larger number of hops when network
size gets larger. According to typical MAC layer protocol like that of IEEE 802.11, packets
need to wait at each hop to get access to the medium. Since there are more number of hops and there are more overhead in the network for larger network, there will be more contention among the nodes to get access to the medium. Hence packets need to wait for longer period of time at each hop. The delay performances of a network carrying more number of connections are also shown in Figure 2.11. It is shown that for a given network size, the delay per packet increases with the number of connections. For example, when network size is 100 nodes and there are five connections operating in the network, the delay per packet is 0.02 second. For the same network size, when there are 10 connections and 20 connections, the delay per packet increases to 0.02 second and 0.022 second respectively. The differences in delays become more evident when network size is 300 nodes. For that network size, the delay per packet are 0.04 second, 0.044 second and 0.055 second when there are 5 connections, 10 connections and 20 connections respectively.

To investigate the throughput performance of the network, a network topology of 50 nodes were created. The network area was 1000m x 500m. The network connections were similar to those of previous simulations. But the packet generation rates were varied from...
1 packet/sec to 8 packet/sec. The throughput performance of the network is shown in Figure 2.12. The throughput performance is measured as the number of data packet successfully delivered to the destination. In that figure, it is depicted that the throughput increases as the packet generation rate is increased. When packet generation rate is 1 packet/second, the number of packet delivered to the destination is 3998. That number increases to 7975, 12291, 12945 and 13553 when packet generation rate increases to 2, 4, 6 and 8 packets per second respectively. Initially the throughput increases linearly with the packet generation rate when the packet generation rate was in the range of 1-4 packets/second. But after that throughput does not increase linearly with the packet generation rate. That kind of network performance conforms to the fact that wireless network has a capacity limit [25]. A wireless network can bear traffic to a certain limit and after that limit network throughput decreases. That kind of limit is depicted in Figure 2.12 when network size was increased by keeping the same node density and when the similar connections pattern were maintained in the network. From that figure, it can be concluded that the capacity limit of a network decreases with the network size. For example, when network size is of 100 nodes, the max-
imum number of packet delivered to the destination is 10736, but the maximum number of packet delivered to the destination decreases to 8757 when network size is of 200 nodes.

Based on the simulation results presented in this section, the performances of DSR protocol can be summarized as follows:

- Overhead packets generated by DSR protocol depend on the number of nodes as well as the number of connections in the network.

- Overhead packets can occupy a considerable portions of bandwidth. Hence useful data packet suffers longer delay if there are large number of overhead packets generated in the network.

- Network throughput performance is affected by the network size. Hence DSR protocol does not scale well.

- Network throughput decreases if network traffic increases beyond a certain limit.

In this dissertation, the performance of DSR protocol is improved by reducing the overhead packet generated during the 'flooding' mechanism. The approach used to reduce overhead is to introduce hierarchy among network nodes. The proposed protocol is called Hierarchical Dynamic Source Routing (HDSR) protocol. HDSR protocol uses a cross layer design elements so that nodes that are located in the less congested areas of the network participate in the route discovery mechanism. In that cross layer design the MAC layer congestion information has been used in the network layer. HDSR protocol has been modified to implement Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) protocol. The main objective of HMEDSR protocol is to save node energy so that network life is maximized. HMEDSR protocol also uses a cross layer design, in which network layer and physical layer interact with each other to determine the transmit power level of a node. Fair load distribution among network nodes has been ensured by interacting network layer and MAC layer. It is shown in this dissertation that by using cross layer interactions among protocol stacks local information of nodes can be used to develop efficient routing algorithm. Cross layer design has been an active research focus for the last couple of years. In
the following section, cross layer design has been defined and explained with some examples to understand the concept of cross layer design.

2.11 Cross layer design for MANET

Recently there have been increased interests in protocol design for MANET that rely on interactions between various layers of protocol stack. That kind of interactions among protocol stacks are called "cross layer" design. The researchers, who are proponents of cross layer design, argue that MANET needs to meet diversified Quality of Service (QoS) requirements depending on the applications. Some of those applications of MANET are personal network, home network, sensor network, device network and distributed control system. Each of those applications has its own unique characteristics and service level requirements. For example, personal network consists of laptops, palm tops and personal digital assistants. The usual type of communication pattern in personal network would be peer-to-peer. That kind of communication needs to support diversified requirements (i.e., data rate, delay and reliability). The usual type of communication pattern in home network would be among network devices such as desktop computer, lap top, cordless phone, security devices, consumer electronics and entertainment system. Some of those home network devices have limited battery. The data rate requirements vary when those devices communicate with each other. For example, communication between a palm top to a stereo needs very low data rate. On the other hand, communication between an entertainment center and desktop computer may need high data rate to support high quality video transmission. In device network short range communication usually occurs among small and energy limited devices such as cell phone, modem, printer and projectors. Device network is mainly focused on replacing wired communication with wireless communication. Sensor network consists of large number of sensor nodes which are deployed in an area to collect information about an event. Sensor node has very limited battery power as well as very limited processing power. Data aggregation and reliable data transmission are the main design issues in sensor network. In distributed control system industrial process monitoring is the main objective. Communication between control unit and actuator, process sensor
and control units are the examples of distributed control system. Reliable and time sensitive communication are the main focus in distributed control network.

In addition to those applications, there should more applications coming in future such as military and biomedical applications. Since MANETs are considered suitable for diversified applications and those applications need to support diversified system level Quality of Service (QoS) requirements, it is widely suggested by the researchers that a fixed protocol stack (i.e., OSI model), which is shown in Figure 2.13 is not a good choice for MANET. In fixed protocol stack, each protocol layer works independently and does not adapt its performances depending upon the performances of other layers. The researchers, who are working on cross layer design argue that interactions among protocol stacks are required because changing some parameter in one layer may affect the performance of other layer. Let us assume that signal strength weakens between a transmitter and a receiver and hence affect the link capacity. That transmitter can improve the signal strength by increasing its transmit power level. But an increase in transmit power level can affect the routing decision.
in network layer and the medium access control scheme in MAC layer. Because packet will travel longer hop when transmit power level is increased. Since packet now is traveling for less number of hops, the increase in transmit power level can affect routing decision in the network layer. On the other hand, transmission range is also increased if transmit power level is increased. If the transmission range is increased, there will be more number of nodes in the transmission range that will contend for the medium. Hence an increase in transmit power level may affect MAC layer operation too. The cross layer architecture has been proposed in [24], which is illustrated in Figure 2.14. That figure shows that there are some system level constraints for a given network. Protocol stacks should adapt their performances to meet those constraints. Hence there is a need to optimize performances of individual layer as well to optimize performances of different layers jointly. For those kind of optimizations, the following basic questions need to be answered:

- Which layer should respond to channel variations?
- What are the layers that should be jointly optimized?
- What information should be exchanged among layers?
- How should this information be used by adaptation protocols at each layer?
What are the trade-offs between performance versus complexity and scalability?

A number of research activities on cross layer design have been published in the literature. Those publications have been surveyed and summarized in [62]. Challenges, design complexities and implementations of cross layer design have been outlined in that survey work. Some of the examples [58, 82, 83, 87] of cross layer design that are related to this dissertation have been presented here to explain the concept of cross layer design.

Cross layer design for improving multi-media support has been presented in [83]. MAC layer rate adaptation based on signal strength at the physical layer and routing decision based on congestion information of MAC layer have been proposed in [83]. IEEE 802.11 MAC layer scheme has been modified to implement that rate adaptation scheme. Request-to-Send (RTS) and Clear-to-Send (CTS) packet are used for determining the signal strength of a link. Since signal strength in MANET varies with time, the weighted average method has been used for determining signal strength. Mapping between signal strength indicator and rate is done according to a set of threshold values that are recorded in a table, which is shown in Figure 2.15. The rate adaptation scheme has been tested by using $M-QAM$ modulation scheme. Where $M$ is varied with the signal strength. In congestion aware scheme, MAC layer congestion information is used in the network layer to choose a route, which lies in the less congested area of the network. The authors used two metrics for determining congestion information. MAC layer utilization is used as one metric and instantaneous network interface queue size is used in another metric. Basic route discovery mechanism of DSR protocol has been modified to implement congestion aware routing. When a node receives a route request packet, it determines the congestion around it and if the congestion is less than a threshold, a node forwards that request to other node, otherwise it does not forward that request.

A novel cross layer routing scheme has been proposed in [82], which uses physical layer Signal to Interference and Noise Ratio (SINR) and MAC layer delay in the network layer to make efficient routing selection. In that routing selection process, the selected route has wide bandwidth and less congestion. The authors suggested that physical layer, MAC layer and network layer all contend for the medium. The transmission power and rate at physical
layer affect network layer and MAC layer. The authors argue that MAC layer bandwidth and delay can be used in the routing decision at network layer. By choosing appropriate routing decision at network layer can affect the performances of MAC layer and physical layer. That is why authors suggested in [82] that cross layer interactions among those three layers are essential for routing decision. A cross layer model presented in [82] is shown in Figure 2.16. The authors suggested that the link delay is determined by contention, packet length, number of packets in network interface queue, and channel rate. That link delay is used as routing metric. Network nodes exchange link delay information among themselves by broadcast messages. Destination Sequence Distance Vector (DSDV) is used for that information exchange. DSDV protocol has been modified to include a routing decision based on link delay. Simulation results show that the modified DSDV protocol improves the end-to-end delay of a network by 50% and hence network throughput is improved by 60%.

Congestion-adapative routing protocol has been proposed in [72]. The authors argue that congestion unawareness in routing protocol can cause long delay, high overhead and high packet loss in the network. In on-demand routing protocol like DSR, there is a time delay between the detection of congestion along a route and the discovery of alternative

<table>
<thead>
<tr>
<th>Rate (MBPS)</th>
<th>Pr Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (discard)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>1</td>
<td>1&lt;=Pr &lt;40</td>
</tr>
<tr>
<td>2.5</td>
<td>40&lt;=P &lt;= 150</td>
</tr>
<tr>
<td>2.0</td>
<td>150&lt;=P &lt;= 1e4</td>
</tr>
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<td>1e4&lt;=P &lt;= 2e5</td>
</tr>
<tr>
<td>3.5</td>
<td>2e5&lt;=P &lt;= 1e8</td>
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</tr>
<tr>
<td>6.0</td>
<td>&gt;=1e9</td>
</tr>
</tbody>
</table>

Figure 2.15: Rate adaptation based on signal strength indicator
2. BACKGROUND

Network Routing Decision Delay Rate Physical Channel

Figure 2.16: Cross layer routing realization

route. If alternative routes need to be discovered, there will be more overhead generated in the network. Many packets could have been lost by the time the congestion is detected. The proposed routing protocol called Congestion-adaptive Routing Protocol (CRP) has been proposed in [72] to improve delay by avoiding congested routes. In CRP each node along a route warns its previous node about the congestion. After receiving congestion information, the previous node initiates a route "by pass" algorithm to avoid congested node in the route discovery mechanism. The authors suggested that a number of metrics can be used to monitor congestion such as the number of packets discarded because of limited link buffer capacity, the average queue length, the number of packet times out and re-transmission, the average packet delay and the standard deviation of packet delay. Among those metrics, the authors use the ratio between the current number of packets waiting in the buffer and the size of the buffer. Depending on that ratio, the authors classify nodes into different classes such as 'red' (i.e., nodes are already congested), 'green' (i.e., nodes are far from congested) and 'yellow' (i.e., nodes are not far from congestion).
When a node becomes 'yellow' or 'red' along a route, it sends an update packet to its previous node about the possible congestion. The previous node then discovers a route to bypass the node that is congested. The performance of CRP has been compared with that of DSR and AODV protocols. The simulation results show that CRP improves delay and delivery ratio compared to DSR and AODV protocol.

[28] suggested that a node can measure its congestion information by monitoring the network interface transmission queue length and the MAC layer behavior. The authors have defined two metrics for congestion information: (1) MAC layer utilization, and (2) instantaneous transmission queue length. The MAC layer utilization has been measured by a node to be the fraction of time that node either has (1) one or more packet to transmit in the transmission queue for that network interface or (2) that node has attempted to transmit a packet but it failed. Since the instantaneous MAC layer utilization is either '1' or '0', the author averages those instantaneous values for a period of 10 seconds. The other metric used to measure congestion is the instantaneous transmission queue length. Those congestion metrics are used in the network layer to discover routes that are not congested. The simulation presented in [28] shows that the delay per packet can be improved when congested routes are avoided while making routing decisions. In addition to improving delay, congestion information can be used in a meaningful way in other layers too. For example, information on the congestion at a node or along a path can be used to adapt some traditional functions of the presentation layer such as data compression. If the congestion level indicates that a route is congested, a source node could decide to compress the data before transmission. The authors also suggested that there is a trade off between the bandwidth used for transmission versus the CPU time consumed for compression and decompression and the latency in time taken for these functions.

Those cross layer examples just mentioned show that cross layer design can improve the performances of MANET. But cross layer design has some disadvantages too. Those disadvantages of cross layer design have been investigated in [35]. Some of the major disadvantages are:

- It is hard to characterize the interactions between protocols at different layers.
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- Joint optimization across layers may result in complex algorithm.
- Design an individual protocol needs to consider the functions of other protocol stack.

2.1.2 Conclusion

In this chapter, Mobile Ad hoc Network (MANET) has been defined. It is shown how MANET differs from a traditional wired network, why a good routing protocol is important for MANET and what are the characteristics of a good routing protocol. The operations of proactive and reactive routing protocols have been explained with some examples. 'Flooding' problem of reactive routing protocol has been defined and explained. It is shown how 'flooding' problem affects the performances of the DSR protocol. Cross layer design has also been explained in this chapter. It is shown why cross layer design is important for MANET, how cross layer design can be implemented, what are the advantages and disadvantages of cross layer design.
Chapter 3

Hierarchical DSR (HDSR) protocol

3.1 Introduction

Routing protocols have been proposed to reduce 'flooding' effects in MANET. Those routing protocols reduce overhead generated in the network and hence improve scalability of the routing. Those proposals can be classified as (i) probabilistic schemes such as [26, 37, 52], and [61], (ii) location based schemes such as [44, 52], and (iii) clustering and cluster based schemes such as [5, 7, 6, 15, 38, 46], and [52]. [52] has proposed that a host re-broadcasts a message with a probability of \( P \), which is less than 1.0. In routing, the route discovery messages are re-broadcasted with that probability too. [37] has suggested that phase transition phenomenon occurs in wireless ad hoc networks, and this phenomenon has been used to develop probabilistic models for flooding. [61] has explored the phase transition phenomenon but combined with random graph theory to further improve probabilistic models for flooding. A gossip based approach to solve flooding problem has been proposed in [26], which is also a probabilistic scheme, can reduce flooding during the route discovery up to 35%. Such probabilistic approaches reduce the number of nodes that involves in flooding, hence it reduces the overhead. The main problem of probabilistic models is to determine the probability \( P \) at which a host should re-broadcast a message. \( P \) depends on many
network parameters, such as density of the nodes, topology and number of times that a node can hear re-broadcast messages. But the values of $P$ are not available immediately for the nodes. [44] has presented two methods of location based flooding, called 'self-pruning' and 'dominant pruning'. Both methods use neighbors' location information to reduce re-transmission of broadcast messages. Such location information can be provided by systems like GPS (Global Positioning System) but obtaining and disseminating such information needs additional hardware and protocols, which may not be a cost effective solution. [5] has suggested one of the earliest clustering algorithms called Linked Cluster Architecture (LCA). In LCA protocol, nodes have an identification number. When a group of nodes comes within transmission ranges of each other and starts forming a cluster, the node with the highest identification number becomes the cluster head. All nodes located within a cluster are in direct transmission range of that cluster head. Some nodes are in between the two clusters and provide communication between them. Those nodes are called gateways. Because of mobility, nodes in clusters change and this generates new control messages to select new cluster heads, which increases the overhead. [15] has proposed Clusterhead Gateway Switch Routing (CGSR) to improve LCA by reducing number of cluster head changes. [6] has presented two clustering algorithms based on network node movement. One of them is Distributed Clustering Algorithm (DCA), which is suitable for quasi-static networks where movements of the nodes are very slow. The other algorithm is designed for higher mobility called Distributed and Mobility Adaptive Clustering (DMAC). In both of those algorithms, nodes are assigned different weights. Each node is aware of its weight and cluster head selection is based on these weights. In DMAC, when two cluster heads come within the range of one another, the node with lower weight revokes its role as cluster head. Cluster heads have been eliminated in [46]. Eliminating cluster heads solves route centralization problem but the assumption that network topology will not change during cluster formation may not be true. [7] has presented an adaptive routing algorithm using clusters. In that algorithm, network nodes were classified as: cluster leader, gateway and ordinary node. A node's status may change based on the status of the surrounding nodes. One common requirement of above protocols is that they need 'Hello' messages to collect
neighborhood information, which also contributes to overall overhead. Passive clustering has been introduced in [38], which does not use dedicated protocol specific control packets and 'Hello' messages. By monitoring user data packets that piggyback some predefined cluster information, an impromptu 'soft state' clusters are formed. Four states are defined for nodes: Initial, cluster head, gateway and ordinary node. Passive clustering may not be efficient with on demand routing protocols like DSR because there may not be on going data traffic prior to route discovery.

Those solutions of 'flooding' problem show that hierarchy and clustering are efficient techniques to reduce 'flooding' effect. Routing protocols proposed in [5, 7, 6, 15, 38, 46] and [52] show that 'flooding' problem can be minimized if mobile nodes are classified and assigned different functionalities depending upon its class. Although those protocols reduce overhead and improve scalability but require additional control overhead. The approach proposed in this chapter is to generate hierarchy with minimal or, if possible, with no overhead. In order to achieve that, an approach like passive clustering will be investigated during the route discovery phase of reactive routing protocols. Passive clustering classifies nodes into four different states, namely ordinary node, gateway, cluster head and initial node. In reactive routing, nodes only need to decide either to forward a packet for others or not to forward, so only two states instead of four states are sufficient. That is why hierarchical approach proposed in this chapter has only two states, namely Mobile Node (MN) state and Forwarding Node (FN) state. In MN state, a node acts as either source or destination, and in FN state, a node acts as packet forwarder (i.e., gateways and cluster heads). Only FNs participate in the route discovery, and such provision can significantly reduce the routing overhead but selection of FNs is important to provide scalability, and stability (i.e., connectivity) to the network. FN selection needs to be done with minimum overhead during the route discovery phase, and this selection needs to be adaptive. In order to provide those, FN selection mechanism is proposed that works during route discovery phase of the reactive routing and solely relies on route discovery control packets, like route request messages.

Recently wireless networks with cross-layer design elements have been under investiga-
tion to improve the efficiency of the overall network. Some examples are [2, 15, 24, 37] and [58]. In this chapter, cross layer elements in FN selection mechanism will be utilized, namely medium access congestion information will be used in the FN selection. Using congestion information to improve routing efficiency for ad hoc networks has also been investigated by other researchers as well; some are [28] and [72]. In those studies, congestion information is obtained from queues of the network interfaces of the nodes.

The proposed hierarchical routing protocol in this chapter uses congestion information from MAC layer in a way to increase the probability of selecting FNs in less congested areas of the network, so that the efficiency and scalability of the routing will be improved. In order to show the effectiveness of the proposed protocols, FN selection mechanism and hierarchical architecture have been combined with DSR routing protocol to implement Hierarchical Dynamic Source Routing (HDSR). HDSR has been implemented and tested by using a network simulation tool called Network Simulator (NS-2). It is shown via simulations that HDSR significantly improves the routing performance of DSR. During cross-layer implementation, IEEE 802.11 MAC layer protocol in distributed coordination function (DCF) mode is used.

3.2 HDSR protocol

In HDSR protocol, the participating nodes of the network are classified as Mobile Node (MN) and Forwarding Node (FN). MNs initiate route discovery. FNs help MNs find routes. Once the destination receives the request, the destination MN replies back through the FNs to source MN. Then MN starts sending packet to the destination with assistance of FNs. Route maintenance is performed by FNs only since they are the only nodes that benefit from this information other than source node. HDSR adaptively selects 'FNs' from all nodes in the network. In HDSR, a node switches states between MN to FN and FN to MN. HDSR achieves three main goals: (i) it ensures that FNs are selected so that every source node can reach the destination, (ii) it attempts to minimize the number of nodes to respond to a request message, and (iii) FN selection is based on distributed algorithm. HDSR consists of two main mechanisms- FN Selection and FN De-selection. The following sections describe
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those activities.

3.2.1 FN selection

An MN determines if it should become an FN or not when it receives a request broadcast from a source node. The following FN eligibility rule in HDSR ensures that a source can find a route to the destination:

- **FN eligibility rule**: MN should wait for a random back-off period after receiving a request message from the source and it does not hear any node re-broadcasting that request message during that back-off period.

Figure 3.1 gives the flowchart of the FN selection algorithm and Figure 3.2 shows the pseudocode of FN selection algorithm. When a node has a packet to send, it initiates a route discovery mechanism. Neighbouring nodes that hear this request check if this request was processed before, if yes then they ignore the request. If it is not, then they check if there is an unused back-off time in their system, if yes, then they set their timer to the unused back-off time and start their timers. If there is no prior back-off time, then they randomly select a time and start their timer. While timer is running, they check if any other node is re-broadcasting the request. If they hear any re-broadcast before their timers expire, they simply stop the timer, and store the unused time. If the timer expires, then it re-broadcast the request, and mark this request as processed. Random back-off time, \( T_{\text{delay}} \), can be expressed in the following equation:

\[
T_{\text{delay}} = R \cdot K, \tag{3.1}
\]

where \( R \) is uniformly distributed random variable between \([0, 1]\), and \( K \) is a multiplying delay factor. Here \( K \) is an important factor in the stability and efficiency of the algorithm. Figure 3.5 gives the performance of HDSR with differing values of \( K \). The larger values of \( K \) generates less overhead. Section 3.3 will provide further details on this. Figure 3.3 illustrates an example how the FN selection algorithm works. The source node, \( S \), and destination node, \( D \), are out of the radio range of each other. The source node can only reach the destination node through any of MN 1, MN 2, ..., MN n, which are the neighbors.
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Figure 3.1: FN selection algorithm
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1. Received request packet
2. if( request already processed) then
3. /* nothing to do with that request */
4. return;
5. else
6. /* check timer whether it is running */
7. if(timer is running) then
8. set timer to delay;
9. else
10. {
11. select random back-off time;
12. start timer;
13. }
14. endif
15. endif
16. /* listen to ongoing traffic*/
17. if( hear re-broadcast of the request) then
18. {
19. set delay to remaining time;
20. flag the request;
21. return;
22. }
23. else
24. /* check whether timer expires */
25. if( timer expires ) then
26. {
27. switch to forwarding node;
28. return ;
29. }
30. return;
31. endif
32. endif

Figure 3.2: The pseudocode of FN selection algorithm
of the source and destination. As soon as those neighbors receive the route request, they independently employ FN selection algorithm and randomly select back-off time, which are labeled as $T_1$, $T_2$, ..., $T_n$ respectively. Let us assume that the delay time of MN 2 is the smallest of all other nodes' delay times. So MN 2's timer will expire first and it will become FN then re-broadcast the request message to the destination node. As soon as MNs that hear the re-broadcast of MN 2 stop their timers, and store the remaining back-off delays for future use and they also remain as MNs. Those remaining back-off times will be used in the future. The back-off timer will be set to those remaining times when a node receives new request from other source. After receiving the request message, the destination node replies back to the source node through MN 2, now it is actually an FN (FN 2). The source node starts sending data packets to the destination node using the route $S \rightarrow 2 \rightarrow D$.

Some MNs such as MN $n$ may not hear that re-broadcast of MN 2, and may turn into an FN and re-broadcast the request message. The destination $D$ replies back to this request, and source $S$ inserts this alternative route in the route cache. If node 2, which is existing FN, becomes unavailable by any reason, this secondary route, which is $S \rightarrow n \rightarrow D$, can be used.

3.2.2 FN de-selection

FN automatically changes state from FN to MN by overhearing ongoing traffic. The following rule in HDSR ensures that FN that are not utilized will switch to MN and this will
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Figure 3.4: Transition from FN to MN

provide that there will not be more than required number of FNs for the proper network operation.

- **FN de-selection rule:** FN should become MN if it is the source or destination or it discovers that its role as a FN is redundant.

For this operation, a node is able to overhear a packet carrying routing information by operating its network interface in promiscuous receive mode. If the FN discovers that it is no longer needed or if there are routes shorter than the route that it belongs to, it switches to MN. This procedure is depicted in the Figure 3.4. In that scenario, there are two source nodes, $S_1$ and $S_2$, and two destination nodes $D_1$ and $D_2$. All source nodes and destination nodes are mobile nodes. Let us assume that there is an ongoing communication along the path $S_2 - 3 - D_2$ when the source $S_1$ initiates route discovery to find a route to the destination $D_2$. That source finds FNs 1, 2 and 3 located within its transmission range. FN 4 and FN 5 re-broadcast request message when they receive it from FN 1 and FN 3, respectively. As a result the source node discovers three source routes: $S_1 - 1 - 4 - D_1$, $S_1 - 2 - D_1$ and $S_1 - 3 - 5 - D_1$. Since the source node chooses the shortest path, which is route $S_1 - 2 - D_1$, it starts sending packets using that route. FN 1 and FN 5 overhear the
ongoing traffic between S1 and FN 2, then switches back to MN state. But FN 3 does not switch back to MN because another source node, S2, is using a route that FN 3 belongs to.

3.3 Overhead and delay analysis

The FN selection algorithm has been tested in a random network where 60 network nodes are uniformly distributed over an area of $1000m \times 600m$. The network size was increased by keeping the node density constant. One connection was set up between two arbitrary nodes. Only those simulation results were counted where the packet travels for more than one hop. The overhead reduction of that scenario is shown in Figure 3.5. From that figure, it can be concluded that the number of route request message increases linearly with the network size. But the number of request message is always less in HDSR than in DSR. The number of request messages depends on the value of $K$. Although, the greater value of $K$ reduces overhead, it also delays finding routes since it delays sending route request messages. The value of $K$ was equal to 10 for the other experiments and their results are presented in
In those simulations, mobile nodes were randomly distributed over a flat area according to uniform distribution. In this chapter, all the simulations carried out while the network nodes were static. Node densities were kept constant when the number of MNs in the network was increased. For example, if the area is 1000m x 500m when the number of MNs is 50, the area is 1000m x 1000m when the number of MNs is 100 and the area is 1500m x 1000m when the number of MNs is 150. Traffic sources are Constant Bit Rate (CBR) with 512 bytes per packet. The source-destination pairs are placed randomly over the network but the number of pairs was constant during each simulation scenario. There are 20 pairs of connections in each simulation. Each CBR starts at random time and each simulation was run for 250 seconds. The packet generation rate was 2.0 packets/sec. In order to increase the statistical reliability of the simulations, each scenario is simulated 10 times with different node topologies, which are constructed randomly. The reported results are average of these 10 simulations.

Figure 3.6: Broadcast reduction with 20 connection
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Figure 3.7: Delay reduction in HDSR with 20 connection

Figure 3.8: Delivery ratio comparison of DSR and HDSR protocols
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Figure 3.6 shows how the number of request re-broadcast messages\(^1\) in both protocols differs. From that figure, it can be concluded although the overhead reduction is not significant for small network, but that overhead reduction in HDSR protocol is more significant when network size is large. For example, the number of overhead per data packet is almost same in both DSR and HDSR protocol when network consists of 50 mobile nodes. When the network consists of 150 mobile nodes, the number of overhead per data packet is .15 in HDSR protocol. But the number of overhead per data packet is 1.2 in DSR protocol. Hence almost 85% of overhead is reduced. The delay performances of DSR and HDSR protocols are compared in Figure 3.7. In DSR protocol, the delay per packet is 0.2 second, 4.0 second and 5.8 seconds when network sizes are 50 nodes, 100 nodes and 150 nodes respectively. In HDSR protocol, those delay figures are 0.19 second, 1.1 second and 1.3 second for similar network sizes. Although delay performances are similar in DSR protocol and HDSR protocol when network size is 50, there are delay improvements of 75% and 80% when network sizes are 100 nodes and 150 nodes. The delivery ratio of DSR protocol and HDSR protocol are compared in Figure 3.8. The delivery ratio is defined as the ratio between number of packets delivered to the destination and the number of packets sent by the sources. In DSR protocol, the delivery ratios drop from 80% to 55% when network size increases from 50 nodes to 150 nodes. In HDSR protocol, the delivery ratios drop from 88% to 82% only. Hence it can be concluded that HDSR protocol shows better performance in terms of delivery ratio compared to DSR protocol. That means HDSR protocol has less number of packet loss compared to DSR protocol. The simulation results presented in this section show that HDSR reduces overhead, improves delay and delivery ratio. In order to further improve delay performance, it is imperative that FNs located in the less congested area need to be selected during the route discovery process. In order to determine the congestion level, MAC layer congestion information was used for selecting FNs, which is described in the following section.

\(^1\)Number of route reply messages are negligible compared to number of request messages since they are unicast packets, that’s why they are not included in the figures.
3.4 Cross-layer design in FN selection

[72] suggested that a variety of metrics can be used for a node to monitor congestion status. Some of those are the percentage of all packets discarded for lack of buffer space, the average queue length, the number of packets that cause timed out and need to be retransmitted, the average packet delay, and the standard deviation of packet delay. The authors defined the congestion status of a node as the ratio \( r \) between the number of packets currently buffered and the buffer size in [72]. They proposed a routing algorithm to by-pass more congested node in the route discovery path so that routes are selected in less congested portion of the network. [28] used two metrics to measure the level of congestion at a node. The first metric is the average MAC layer utilization level at a node and the second metric is the instantaneous network interface queue size. Those congestion metrics are used to reduce congestion in the network.

In the cross layer designed proposed for improving the performance of HDSR protocol, the MAC layer contention window indicates the measure the congestion level around that
node. The IEEE 802.11 MAC layer protocol provides asynchronous and time-bounded medium access control on a variety of physical layers. The basic access method in the IEEE 802.11 MAC protocol is the Distributed Coordination Function (DCF), which employs a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. To ensure the smooth and fair functioning of this algorithm, DCF includes a set of delays that amounts to a priority scheme. The CSMA/CA medium access control logic of IEEE 802.11 is shown in Figure 3.9.

When a station has a frame to transmit, it senses the medium. If the medium is idle, it waits to see if the medium remains idle for a time equal to Short Inter Frame Space (SIFS). If so, the station may transmit immediately. If the medium is busy (either because the station initially finds the medium busy or because the medium becomes busy during IFS idle time), the station defers transmission and continues to monitor the medium until the current transmission is over. Once the current transmission is over, the station delays another SIFS. If the medium remains idle for this period, then the station backs off a random amount of time and again senses the medium. If the medium is still idle, the station may transmit. During the back off time, if the medium becomes busy, the back off timer is halted and resumes when the medium becomes idle. The medium access mechanism is refined by using another time interval called DCF Inter Frame Space (DIFS). The DIFS interval is the longest SIFS used as a minimum delay for asynchronous frames contending for access. Figure 3.10 illustrates the use of those time intervals in detail. DCF adopts a slotted binary exponential back off technique. The time immediately following an idle DIFS is slotted, a station is allowed to transmit at the beginning of each slot. The back off time is uniformly chosen in the interval (0, CW-1) defined as a back off window (contention window). The back off time is given by:

$$ T_{\text{back-off}} = [R \cdot CW] \cdot T_{\text{slot}}, $$

(3.2)

where $R$ is a uniformly distributed random variable between $[0, 1]$, $CW$ is the contention window and $T_{\text{slot}}$ is the slot time.

When a station receives a frame addressed only to itself (not multi-cast or broadcast),
it responds with an ACK frame after waiting only for a SIFS period. If an acknowledgment is not received, the data frame is presumed to have been lost, and a retransmission is scheduled. For direct-sequence-spread-spectrum technology at 2 Mbits/sec transmission rate SIFS=28 $\mu$S, DIFS=128 $\mu$S, and back off slot time=50 $\mu$S used for our model.

The contention window described in the previous section indicates how the surrounding channel is congested. At first transmission attempt, $CW=CW_{min}$ and then it is doubled at each retransmission attempt up to $CW_{max}$. In the current version $CW_{min} = 32$ and $CW_{max} = 1024$. The back off time given by (3.2) is in the range of $\mu$S because of the multiplying factor $T_{slot}$. In order to use the contention level information in the network layer to form hierarchy, the following two fundamental questions need to answer:

- How should contention level information be exchanged between the MAC layer and the network layer?
- What are the conditions that need to be imposed while using contention level information in the network layer?

The MAC layer parameter such as contention window varies in the range of micro seconds. But the network layer parameter such as interval between two request messages is in the range of second. The different time scales used in those two layers imply that there is a need to rescale the MAC layer information to use in the network layer, which is suggested by [24] too. The rescaling of MAC layer information can be done by eliminating $T_{slot}$ term from (3.2). The delay function of (3.2) can be re-written as:

$$T_{delay} = R \cdot CW,$$

Figure 3.10: Basic access mechanism in IEEE 802.11
From (3.3), it can be concluded that those network nodes that have higher contention windows will have longer delays compared to nodes that have smaller contention windows. The contention window $CW$ information available in the MAC layer is transferred to the network layer by storing the value in the packet header. It is predicted that nodes that are located in less congested section of the network has smaller $CW$, and those nodes will have more chances of becoming FN. This provision will allow network to distribute traffic more evenly and eliminate the network congestion.

In order to use MAC level congestion information, some conditions have been imposed in the network layer. The reason is that when the network is not congested, there is no need to select nodes in the congested area. In order to adapt FN selection algorithm to handle low traffic rates, the delay time was initialized to zero second. FN selection algorithm should work when there is congestion in the network otherwise it should behave like regular DSR. When the network congestion exceeds some threshold value, node should execute FN selection algorithm. During the testing of the protocol, several threshold values were tested.

Figure 3.11: Effects of threshold on delay
and a threshold value of 16.0 seconds was arbitrarily set in all simulations. The effects of threshold on delay performance is shown in Figure 3.11. That figure depicts the delay performance of a network under low traffic condition for DSR protocol, HDSR protocol without thresholding and HDSR protocol with threshold. Figure 3.11 shows that the delay per packet is lowest in DSR protocol. If no threshold is used, the delay per packet is higher in HDSR protocol compared to DSR protocol. When a threshold was imposed in HDSR protocol, the delay per packet is reduced. Hence setting a threshold value improves delay performance under very low traffic condition in the network.

3.5 Performance evaluation

New proposed protocol was implemented and tested by Network Simulator 2 (NS-2) [20]. In NS-2, the effective transmission range of wireless radio is 250 meters. To compare the performance of the proposed protocol and the traditional DSR protocol, the following performance metrics were used:

- Data Packet: the total number of data packet received at the destinations.
- Delay: delay per received data packet.

To measure how the cross layer design handles the varying traffic loads, a simulation scenario of 200 mobile nodes was created, where mobile nodes were randomly distributed over a flat area of $2000m \times 1000m$. The traffic generation of sources was varied between 0.50 packet per second and 8.0 packets per second. The performance of the network in terms of data packet successfully reached the destination is depicted in Figure 3.12, which shows that DSR can only carry up to 4.0 packet/sec data rate. After that network is saturated and it can not carry more traffic. But HDSR can carry traffic loads up to 8.0 packet/sec. HDSR can handle more traffic load compared to regular DSR except in very low traffic rate. It is shown in that figure that both DSR and HDSR protocol shows similar performance when packet generation rate is in the range of 0.5 to 2.0 packet per second. After that, HDSR protocol shows better performance compared to DSR protocol. For example, when
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**Figure 3.12:** Data packet delivered with varying load

**Figure 3.13:** Delay Comparison with varying network size

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packet generation rate was 8 packet/sec, the HDSR protocol delivered 14369 packet to the destination. But DSR protocol delivered only 7863 packets to the destination. Hence HDSR protocol can carry 1.5 times more traffic than DSR protocol. The delay comparison of that scenario is shown in Figure 3.13. That figure shows that there is a significant delay improvements in the network when there is more traffic. In DSR protocol, the delay per packet is 8.0 when traffic generation rate is 8 packets per second. But that delay is only 4.5 second in HDSR protocol. Hence there is almost 50% less delay in HDSR protocol compared to DSR protocol. That figure also shows that the delay performances for DSR protocol and HDSR protocol are almost similar for small traffic rate. Those kinds of improvements are achieved because HDSR avoids more congested sections of the network while selecting FNs.

3.6 Conclusions

This chapter presents a hierarchical approach to improve the efficiency of routing for mobile ad hoc networks. The network nodes are classified as mobile nodes, and forwarding nodes. Forwarding node selection algorithm is introduced. This algorithm works in distributed fashion and dynamically at each node. Two different versions of the selection algorithm are introduced, one is random, and the other one is based on cross-layer design. Both versions work on demand and require no additional control messages in order to operate. It used routing discovery messages and MAC layer contention information. Hierarchical architecture and FN selection algorithm for Dynamic Source Routing have been implemented. The new algorithm is called as Hierarchical Dynamic Source Routing (HDSR). The experiments reveal that HDSR significantly improves throughput performance of the network by reducing the control overhead and also by avoiding network 'hot spots' while selecting routes. HDSR performs better when network size is large and also when traffic load is higher.
Chapter 4

Energy Saving DSR (ESDSR) protocol

4.1 Introduction

Mobile Ad hoc Network (MANET) is consist of battery-operated computing devices, which cooperate with each other to transmit packet from a source node to a destination node. The availability of each node is equally important for the enforcement of that kind of cooperation. The failure of a single node can greatly affect the network performance. Since mobile nodes are usually battery-operated, one of the major reasons of node failure is battery exhaustion. In order to maximize the life-time of a mobile node, it is important to reduce the energy consumption of a node while transmitting packets. In recent years, a number of studies have been done to achieve energy conservation in MANET. Those can be broadly classified as transmit power control approach protocols [8, 13, 18, 40, 50] and [63], and load distribution approach protocols [70] and [80]. The transmit power control approach protocols determine the optimal routing path that minimizes total transmission energy required to deliver data packets from a source to a destination. The load distribution approach protocols focus on balancing energy usage among the nodes by avoiding over-utilized nodes while selecting a routing path. There is no clear consensus that any particular protocol or a class of protocols are suitable for all scenarios. In this chapter an Energy Saving Dynamic Source Routing
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(ESDSR) protocol has been proposed for MANET. The ESDSR protocol integrates the advantages of transmit power control approach protocol and load distribution approach protocol. In ESDSR, the nodes that have 'tendency' to 'die out' very soon are avoided during the route discovery phase of this protocol. The 'tendency' of the node to 'die out' is expressed quantitatively as the ratio of the remaining battery energy and the current transmit power of the node. That ratio is called 'expected life' of the node. Once the routing decision is made, link by link transmit power adjustment is accomplished depending on the signal strength at which a node receives a packet.

4.2 ESDSR protocol

The DSR protocol has been modified to implement ESDSR protocol. The routing decision of DSR is based on the shortest hop algorithm. That routing decision of DSR protocol has been modified to save energy. The resultant protocol is called ESDSR protocol. In ESDSR, the mobile nodes, which are very likely to drain out of batteries are avoided in the route discovery phase of protocol. The energy level and the transmit power level of a node are taken into account while making routing decision. The ratios of current energy levels and the transmit power levels of nodes indicate how likely those nodes will deplete battery. In order to do that a source node finds a route $R(t)$ at time $t$ such that the following cost function is maximized:

$$C(R, t) = \max (R_j(t))$$  \hspace{1cm} (4.1)
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\[ R_j(t) = \min \left( \frac{E_i}{P_{ti}} \right) \quad (4.2) \]

where, \( R_j(t) \) is the minimum energy to transmit power ratio for the path \( j \), \( E_i \) is remaining energy of node \( i \) on the discovered path and \( P_{ti} \) is the transmit power of node \( i \) on the discovered path.

Route discovery mechanism in ESDSR is illustrated in Figure 4.1. Node 1 is the source node and Node 5 is the destination node. Assume that all nodes have empty caches. The energy levels of the nodes and their current transmit power levels are shown in the Figure 4.1 at time \( t \), when the source initiated the route discovery. The source initiates a route discovery by broadcasting the route request packet. Node 2 and Node 4 are within the transmission range of Node 1. Since intermediate nodes 2 and 4 are not the destination, those two nodes add their own node ids in the request packet and re-broadcast that route request packet. Once the destination node, Node 5 receives the route request packet, it sends a reply to the source node, Node 1 by reversing the path through which it receives the request packet.

Let us assume that the destination node replies back to the source node using the route 5 — 3 — 2 — 1. When the intermediate node such as Node 3 receives the reply packet it estimates its 'expected life' using \( \frac{E_i}{P_{ti}} \) and let us assume this value is 0.2. Node 3 records this value in that reply packet and forwards the reply packet to next hop, which is Node 2. Node 2 estimates its 'expected life' using the same formula. Let us assume that value is 0.1. It also reads the value recorded in the reply packet (which is 0.2). Node 2 replaces the 'expected life' recorded in the reply packet because its 'expected life' is less than that recorded in the reply packet. Thus the reply packet carries the value of the 'minimum expected life' of the path 1 — 2 — 3 — 5 which is equal to 0.1. The source node records this path in the cache. Let us assume that the source node discovers another path 1 — 4 — 5 which has minimum 'expected value' of 0.05. The source then selects the path 1 — 2 — 3 — 5 because that path has higher 'minimum expected life' instead of choosing the shortest path 1 — 4 — 5. But DSR protocol always chooses path 1 — 4 — 5 because it is the shortest path.

Once a source discovers paths and selects a path as mentioned above, it starts sending...
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data packet using that route. Once a routing decision has been made, link by link power
adjustment need to be accomplished in the following way. Every node records its transmit
power in the data packet and sends that data packet to the next hop. When the next hop
receives that data packet at power $P_{\text{recv}}$, it reads the transmit power $P_{\text{tx}}$ from the packet
and recalculates the transmit power for the previous hop using the following formula

$$P_{\text{min}} = P_{\text{tx}} - P_{\text{recv}} + P_{\text{threshold}}$$

(4.3)

where all the values are in dBW. $P_{\text{threshold}}$ is the required threshold power of the receiving
node for successful reception of the packet. The typical value of $P_{\text{threshold}}$ in LAN 802.11
is 3.652$^{-10}$ Watt. To overcome the problem of unstable links due to channel fluctuations, a
margin $P_{\text{margin}}$ in dBW is included in (4.3). Hence (4.3) becomes

$$P_{\text{min}} = P_{\text{tx}} - P_{\text{recv}} + P_{\text{threshold}} + P_{\text{margin}}$$

(4.4)

The recalculated transmit power is recorded in a power table. Each node maintains a
power table, which records the target node's ID and the transmit power for this target node.
The recalculated transmit power is recorded in the MAC packet (ACK packet). When the
ACK packet is received by the transmitting node, it records the modified transmit power
in the power table and transmits packet at that power.

In the experiments conducted to test the performance of ESDSR protocol, a margin
of 1 dB was maintained. Usually a margin of 3 dB has been maintained in [18]. Since in
ESDSR the transmit power is monitored packet by packet, a margin of 1 dB was maintained.
The advantages of our packet by packet monitoring is that if channel conditions changes
during the packet transmission, the transmit power also changes accordingly. Since ESDSR
protocol maintains a small margin, it can save more energy than the protocol mentioned
in [18].

The power table of a mobile node is updated each time when a node receives a packet
from its neighbor. When a node has some packet to send to a node, it searches its power
table to find the required transmit power for that node and transmits packet at that power.
When a node can not find a record in the power table for a particular node (which will be

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Figure 4.2: Transmit power variation with distance

Figure 4.3: Energy saving per packet in two node situation
the case when two nodes never exchanged packet before), it transmits at default power level which is 280 mW for 250 meters range. In order to maintain the full functionality of route discovery and route maintenance of DSR, all routing packets (route request, route reply) are transmitted at default power. Moreover, in order to maintain normal operation of MAC layer, all MAC layer packets (RTS, CTS, ACK) are transmitted at that default power too.

To conceive how much energy saving can be achieved by adjusting transmit power as mentioned above, let us consider a scenario with two nodes where there are only a source node and a destination node. The source node adjusts its transmit power according to (4.4). In order to observe the effect of power adjustment on energy consumption, a model mentioned in [18] is used. The energy consumption per data-packet of size $D$ bytes over a given link can be modeled as-

$$E(D, P_t) = K_1 P_t D + K_2$$

(4.5)

Typical values of $K_1$ and $K_2$ in 802.11 MAC environment at 2 Mbps bit rate are $4 \mu$Sec. per bytes and $42 \mu$J respectively. The variation of transmit power with respect to distance is depicted in Figure 4.2. The energy saving due to the controlled transmit power is shown in Figure 4.3. It is clear from that figure that almost 70% of energy can be saved if controlled transmit power is used instead of fixed transmit power.

### 4.3 Simulation model

For simulations, NS-2 [20] was used with the CMU wireless extension. DSR routing protocol with flow state disabled was used. The tap function was also disabled. Since the receiving power is constant and a fixed amount of energy is dissipated when a node receives the packet, receiving power consumption was set to zero. The medium access control (MAC) protocol was based on IEEE 802.11 with 2 Megabits per second raw capacity. The 802.11 distributed coordination function used Request-To-Send (RTS) and Clear-To-Send (CTS) control packets for unicast data transmission, and implemented a form of virtual carrier sensing and channel reservation to reduce the impact of hidden terminal problem. Data transmission was followed by an ACK. For radio propagation model, a two-ray path loss
model was used. The traffic sources were Constant Bit Rate (CBR) with 512 bytes per packet. The node structure provided with NS-2 was modified to include a power table. The structure of packet header was modified to carry data about the transmit power and the threshold power of a node. Route cache was modified to store additional information about the 'expected life' of the nodes for a path. Routing decision logic of DSR was changed to energy aware decision logic. The energy model was modified to implement (4.5) for energy consumption while transmitting packets.

A static scenario of 40 mobile nodes were randomly distributed initially in an area of 200m × 200m (a square area). The source and destination pairs were spread randomly over the network but the number of pairs were kept constant during each scenario. Each CBR source started randomly at the first 0 to 10 seconds of the simulation and each simulation was run for 250 seconds. The number of connections was 20 in our case. The network area was varied to 300m × 300m, 400m × 400m and 500m × 500m while keeping the number of mobile nodes and connections constant. The total energy consumptions of the nodes and the number of dead node at the end of simulation were measured. An initial energy of 1.0 Joule was assigned to each node. To compare the performance of the proposed ESDSR protocol and the traditional DSR protocol, the following performance metrics were used:
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- Througput: It is measured as total number of useful data packets reached the destination at the end of simulation.

- Energy Consumption per packet: It is measured as the ratio of the total energy consumed for the network to the number of packets successfully reached the destination.

- Number of dead nodes: It is measured as the number of nodes became out of battery at the end of the simulation.

4.4 Simulation results and analysis

In this section, the simulation results and analysis of those results are presented. The ESDSR and DSR protocols are tested in scenario with differing node concentration per unit area. With those tests, the capacity of the network (i.e., how many packets were successfully reached to destination), the energy consumption per packet, how much energy saved in ESDSR and how many nodes are ‘dead’ at the end of simulation are compared with those of DSR protocol. Figure 4.4 shows the number of packets successfully reached the destination. In ESDSR, the packet reached the destination is higher than that of DSR.
The reason is that some nodes were out of batteries during the simulation and hence they could not forward any more packet to a destination. They could not transmit their own packet either. But in ESDSR the nodes have longer lives. So the nodes were capable of transmitting their own packets as well as forward packets for longer period of time. The energy consumption per packet is depicted in Figure 4.5. From that figure, it can be shown that energy consumption per packet is around 0.75 mJ when the network is operating in an area of $200m \times 200m$ using ESDSR protocol. But the energy consumption per packet is around 1.25 mJ for that same network topology using DSR protocol. The energy consumption per packet gets larger when the network area was increased. Since packets are traveling for more hops in larger network area, the energy consumption per packet increases. When the network area is $500m \times 500m$, the energy consumptions per packet in ESDSR and DSR are almost equal. The percentage of energy saving in ESDSR is depicted in Figure 4.6. In that figure it is shown that 37% of energy used in DSR can be saved in ESDSR protocol. The number of dead nodes at the end of simulation is shown in the Figure 4.7. The number of dead nodes is 1 in ESDSR compared to 5 dead nodes in DSR. The number of dead nodes are almost same when the network area is $500m \times 500m$. When the network area gets larger, the transmit power in ESDSR tends to be equal to that.
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4.4 Area (thousand sq. meter)

Figure 4.7: Number of dead node at the end of simulation

of DSR. Hence the number of dead nodes are almost same in ESDSR and DSR.

4.5 Conclusions

In this chapter, an energy saving routing protocol called Energy Saving Dynamic Source Routing (ESDSR) has been proposed. The minimum energy routing protocol is designed and implemented by making changes in the minimum-hop fixed-transmit power version of DSR. Although network life is maximized using ESDSR protocol, including extra information in the packet header changes packet structure and increases packet size. Modifying the IEEE 802.11 MAC layer protocol will cost a change in the network card and firmware. Introducing transmit power control over the transmission medium may cause changes in the power circuits in the radio hardware. Since packets are not sent via minimum hop, the average number of hop will increase. Hence delay may be higher in ESDSR in compare to DSR. How that delay can be reduced needs further investigations. The comparison of ESDSR with other energy aware routing protocol needs to be done in future to fairly judge the performance of ESDSR.
Chapter 5

Hierarchical Minimum Energy DSR (HMEDSR) protocol

5.1 Introduction

In the recent years, there has been growing interest in MANET as a means of providing instant networking to a group of mobile nodes. Those mobile nodes may not be within the transmission ranges of each other because they have limited transmission range. Mobile nodes usually communicate in multi-hop fashion. That is why the availability of each node is equally important to the proper operation of the network. The failure of a single node can greatly affect the overall performance of the network. Since energy source of mobile node is usually battery, one of the major reasons of node failure is the battery exhaustion. In order to utilize that limited resource and extend the life-time of the networks, routing protocols have been proposed for MANET. Those protocols use different approaches to save energy. Those approaches can broadly be classified as: (1) transmit power control [8, 13, 18, 40, 50] and [63], (2) load distribution [70] and [80], and (3) sleep/power-down [14] and [86]. In transmit power control approach, the transmit power of mobile node is controlled to maintain connected topology of the network. The main objective is to find the best route
that minimizes the total energy consumption while transmitting packets between a source and a destination. In [13], the optimal path is selected from a set of paths that minimizes the sum of link costs between a source-destination pair. The link cost is calculated from the initial and the residual battery energies of mobile nodes. In [40], two different parameters of network nodes are optimized: minimizing power consumption and maximizing minimal residual energy. The optimal path is found using the Dijkstra's algorithm. In [63], global information of the network such as data-generation rate or power-level information of all nodes are used in routing decision. Minimum energy routing protocol has been proposed in [18]. The minimum energy routing protocol is based on the fact that a mobile node should transmit a packet at a power level that is just enough to reach the next hop. In [18], a margin of 3 dB was added to the minimum power level to cope with channel randomness and noise. Retransmission-energy Aware Routing (RAR) protocol has been proposed in [8]. In RAR protocol, link error rate has been taken into account to determine optimal transmit power. Smallest Common Power (COMPOW) protocol [50] selects the smallest transmit power level, which is just enough to maintain connectivity of the entire network. Each node selects different power levels and builds routing tables for each power level. By exchanging that routing information among themselves, mobile nodes discover the minimal power level that achieves the connectivity. That kind of routing information exchanges causes extra routing overhead in the network, which may affect the overall performance of the network.

In load distribution approach, network traffic is distributed among nodes to maximize lifetime of network. A quantitative analysis shown in [55] that nodes located around the center of the network carry more traffic than the other nodes that located around the perimeter of the network. Hence there are some nodes that are over utilized or under utilized. The load distribution approach reduces the chance of using over utilized nodes while selecting a path to increase the network life-time. Localized Energy-Aware Routing (LEAR) [80] protocol is implemented by modifying the DSR protocol. In LEAR, a mobile node decides whether to forward or not to forward the traffic to other nodes depending upon the residual energy level. If the residual energy level is greater than a threshold, a mobile node forwards the traffic for others. Otherwise, it should not forward. Conditional Max-Min Battery
Capacity Routing (CMBR) [70] protocol is similar to LEAR protocol. There are two techniques applied in selecting the routes. If all the nodes in the route have battery levels larger than a threshold value, the minimum power route among the discovered routes are selected. On the other hand if all nodes in the route have battery levels less that the threshold, routes with the lowest battery levels are avoided. Sleep/power-down approaches can also reduce the energy consumption of nodes in the networks. Routing protocols that coordinate sleep/power-down approaches are proposed to reduce the energy consumption in the network as well. SPAN [14] is one of the routing protocols that utilize sleep/power-down approach. In SPAN, a coordinator, called 'master', is selected. The eligibility rule to be a master is that if two neighboring nodes can not reach each other directly or via one or two masters, they should become master. Once a mobile node becomes a master, it periodically checks if it should withdraw as a master. A non-master or ordinary node also periodically determines if it should become a master. That kind of switching between master and ordinary node ensures that the network traffic is distributed among the nodes.

The 'Hello' messages are used to collect information about the neighbors to decide which node will become the master or which node will become the ordinary node. That kind of 'Hello' messages incur additional control messages in the network. In Geographic Adaptive Fidelity (GAF) [86] protocol, each node uses location information that is obtained from Global Positioning System (GPS) to associate itself with a predeterminate 'grid', and the node that has the highest residual battery power in each grid becomes the master node in this grid. Other nodes located in the same grid go to sleep mode. Providing GPS system to each mobile node may not be a suitable solution in every application scenario specially when mobile nodes have limited resources and processing power.

In this chapter, minimum energy routing protocols called Minimum Energy Dynamic Source Routing (MEDSR) and Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) protocols are proposed for MANET. MEDSR protocol is implemented from Dynamic Source Routing (DSR) protocol by modifying the control messages of DSR protocol. MEDSR protocol works in two phases: route discovery and link-by-link power adjustment. Different power levels are used during the discovery process to identify paths.
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that can return low energy routes in data transmission. In that process, at first, a source node tries to discover a path using low power level. If that source cannot discover a route using that low power level (i.e., transmission radius of 125 meter), it will switch to higher power level (i.e., transmission radius of 250 meter). That kind of route discovery by using two power levels reduces the route discovery time and also reduces overhead compared to COMPOW protocol explained in [50]. The COMPOW protocol uses six different power levels in route discovery and uses extra overhead to exchange routing information among nodes. According to the proposed MEDSR protocol, once routes are discovered by using any of the two power levels, transmit power levels of the nodes along those routes are adjusted link-by-link to minimum levels. With that adjustment, the nodes transmit a packet to other node at the minimum power level that can reach the next hop. This also leads to a cross-layer design. In cross-layer design, the network layer control packet like route request packet is used to determine the transmission radius of a node. Moreover, route reply packets are used for determining minimum transmission power link-by-link. It is shown via simulations that MEDSR reduces energy consumptions in the network compared to DSR. MEDSR protocol is a reactive routing protocol like DSR protocol, and uses 'flooding' during the route discovery phase of the protocol. Flooding creates a huge number of overhead in the large networks, that is why the routing performance is greatly affected. Although those routing overhead packet is usually very small in size, it is shown in later sections that they consume significant energy. In wireless networks, medium access techniques are also employed for carrier sense, collision detection and avoidance. For example IEEE 802.11 uses clear to send (CTS), ready to send (RTS) and acknowledgment (ACK) packets before and after each transmission including routing control packets. It is shown in this chapter that transmitting routing control messages with flooding and MAC packets become dominant source of power consumption in large MANET. In order to curb the energy consumption in control and MAC packets as well as provide energy saving during data packets, Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) is designed. HMEDSR is similar to Hierarchical Dynamic Source Routing (HDSR) [67], but designed to minimize the energy use in transmission. Hierarchical approach limits the number of routing control
packets, and minimum energy approach limits the energy use in HMEDSR protocol. The simulation results show that HMEDSR can reduce overhead as well as save energy using minimum transmit power. With that, HMEDSR protocol can send more data packets to the destination by using same amount of initial energy compared to DSR protocol.

5.1.1 Overhead reduction by HDSR protocol

It was shown in Section 2.6 of this dissertation that during the route discovery phase of DSR protocol, a huge number of overhead is generated in the network. That kind of huge overhead may affect the performance of ad hoc network especially when network size is large. In order to reduce the number of overhead Hierarchical Dynamic Source Routing (HDSR) protocol has been introduced in Section 3.2. A brief description of HDSR protocol has been provided in this section for the continuity of this chapter. The HDSR protocol intends to reduce unnecessary overhead in DSR protocol by using hierarchy. In HDSR protocol, network nodes can be in two states: Regular or Forwarding state. When a node is in regular state, it is called Mobile Node (MN), and when a node is in forwarding state, it is called Forwarding Node (FN). In MN state, a node is either a source or a destination, and in FN state, a node acts as forwarder (i.e., gateways and cluster heads). Only FNs participate in the route discovery and such provision can significantly reduce the routing overhead. A typical scenario in HDSR is shown in Figure 5.1. In that figure the dark nodes are MNs and the other nodes are FNs. The source node $S$ initiates the route discovery in order to find a path to the destination $D$. The dashed lines are shown the re-broadcasts that are eliminated in the hierarchical architecture. Since only the FNs participate in the route discovery process, the source node $S$ discovers two paths $S - E - F - D$ and $S - J - K - L - M - N - D$. The FN selection is passive and on-demand because no additional control packet is required other than the routing overhead packets and nodes perform FN selection when they hear a routing request packet. When a node hears a route request packet, it goes into a random back-off time instead of forwarding that request. That back-off time, $T$, is given by

$$T = R * K,$$  \hspace{1cm} (5.1)
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where $R$ is a uniform random variable in the range of [0, 1.0] and $K$ is some constant. $K$ is actually parameter of number of neighbors and networks size. In [67] $K$ is replaced with contention window parameter in IEEE 802.11 MAC layer to provide a cross-layer approach to routing, and shown that cross-layer approach gives the best routing performance (i.e., delay, throughput and routing overhead) in all scenarios. During that back-off time, if a node hear any broadcast of that request message, it will cancel the timer and will remain as MN. If it does not hear during the back-off time, it becomes FN and forward that request packet to its neighbors. This process goes on until the destination packet receives that request packet. The destination node replies all request packets which arrive through different paths. When a source node receives all the route replies, it stores those routes in its route cache. Then source node starts sending data packet using the shortest path algorithm. That means a source chooses a path that has the least number of hops. In the example as shown in Figure 5.1, after discovering two paths, the source node starts sending packets using the shortest path, so the selected path is $S - E - F - D$. If that route breaks, route maintenance mechanism will be invoked by the HDSR protocol. The source will start using the other path $S - J - K - L - M - N - D$. In order to investigate how routing overhead is reduced by HDSR protocol, a simulation scenario is created. In that simulations, the node density of the network was kept constant but the number of nodes increased from 100 to 300 nodes. The node density was 100 nodes per 1 km$^2$ (i.e., $1000m \times 1000m$). Twenty constant bit rate (CBR) connections were set up randomly in the network. The MAC protocol was IEEE 802.11. The simulations ran for 250 seconds and each case was simulated 5 times with different scenarios and the reported results are average of the simulations. The overhead generated in the network consists of MAC overhead (CTS, RTS, ACK) and routing overhead (route request, route reply and route error). The overhead generated by DSR and HDSR protocol are shown in Figure 5.2. The overhead packets shown in that figure consist of routing and MAC packets per data packet. From that figure it is depicted that when DSR protocol is used, there are 40, 60 and 118 overhead packets per data packet are generated for networks consisting of 100 nodes, 200 nodes and 300 nodes respectively. On the other hand when HDSR protocol is used, there are 20, 25 and 30 overhead packets per data packet.
packet are generated for the similar network sizes. Hence overhead packets are reduced by 2 times when the network has 100 nodes, but overhead packets are reduced by 4 times when the network has 300 nodes. Since a huge number of overhead can be reduced for a large network compared to smaller network, a considerable portion of nodes' energies can be saved by using HDSR protocol compared to DSR protocol.

5.2 Energy consumption model and analysis

The energy consumption in ad hoc network has been investigated in [21] and [18]. Those models are developed by experimenting with actual wireless network interface cards (NICs). The energy spent in the wireless node is parameterized by considering $D$ bytes packet transmitted at $P_t$ power level, denoted by $E(D, P_t)$, which is expressed by

$$E(D, P_t) = K_1 P_t D + K_2,$$  \hspace{1cm} (5.2)

where the values of $K_1$ and $K_2$ are $4 \, \mu$sec/byte and $42 \, \mu$J (5.2) is used for the rest of this study to calculate the consumed energy while sending each packet from the NICs in all simulation scenarios. In order to investigate how much energy is consumed by different packet types, energy consumption by transmission of each type is recorded separately. Those
packets are: data, MAC (i.e., CTS, RTS, ACK) and routing control packet (i.e., route request, route reply and route error). MAC and routing control packets are considered as overhead packets. The number of overhead packets varies with the network size but this growth is not necessarily linear. That is why for large networks, significant amount of energy is consumed during transmission of routing control packets and MAC packets.

In order to investigate the distribution of energy consumption among different packet types, we use energy model given by (5.2) and we measured energy consumption by different types of packets (i.e., data packet, routing packet and MAC packet). The results are presented in Figure 5.3 and the major findings are summarized in Figure 5.4. Figure 5.3 shows energy consumed by each packet type per successful data packet. The data energy per packet is the ratio of total energy consumed by data packet and total data packet delivered to destination. The MAC energy per packet is the ratio of total energy consumed by MAC packet and total data packet delivered to destination. The routing energy per packet is the ratio of total energy consumed by routing packet and total data packet delivered to destination. It is depicted in Figure 5.3 that energy consumptions per data packet are 2.8 mJ, 5.5 mJ and 6.8 mJ when network consists of 100 nodes, 200 nodes and 300 nodes. The MAC energy consumptions per data packet are 2.8 mJ, 4.5 mJ and 6.2 mJ for the similar
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Figure 5.3: Energy consumption per data pkt

<table>
<thead>
<tr>
<th>node</th>
<th>Data</th>
<th>MAC</th>
<th>Routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>60</td>
<td>34</td>
<td>6</td>
</tr>
<tr>
<td>200</td>
<td>46</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>300</td>
<td>37</td>
<td>34</td>
<td>29</td>
</tr>
</tbody>
</table>

Figure 5.4: Percentage of total energy consumption by categorization
network size. The routing energy consumptions per data packet are 0.2 mJ, 2.0 mJ and 5.5 mJ. We can conclude that energy consumptions by different types of data packet increases with the network size. The reason of increase in energy consumption is that more nodes are involved in network operation when network size gets larger. But the percentages of total energy consumption by different packet types differ considerably with the network size. The percentage of energy consumptions by different types of packet are shown in Figure 5.4. From that figure, it is depicted that 60% of total energy is consumed by data packet when network consists of 100 nodes. The other 40% of energy is consumed by overhead packets. The total energy consumption by data packets reduces to 37% when network consists of 300 nodes and the major portion of node energy is consumed by overhead packets. Hence a major portion of node energy can be saved if routing overhead is reduced.

In this chapter, routing protocols that reduce energy consumption have been proposed in the network in two folds. Energy consumption by data packet is reduced by an energy aware routing protocol called Minimum Energy Dynamic Source Routing (MEDSR) protocol. Energy consumption by overhead packet is reduced by using a hierarchical routing protocol called Hierarchical Dynamic Source Routing (HDSR). In the next section the MEDSR protocol is introduced, which reduces energy consumption by reducing transmit power level to a minimum value. In the previous section the HDSR protocol was introduced, which reduced the total number of overhead in the network. Hence total energy consumption by overhead packet is reduced. The MEDSR protocol and HDSR protocol were combined together and a new protocol called Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) protocol is introduced. The objective of the HMEDSR protocol is to save energy as well as to reduce overhead in the network.

5.3 Background of minimum energy routing Protocol

In MEDSR protocol transmit power levels of nodes are controlled to minimum levels. There are two main reasons for controlling transmit power to a minimum level: (1) transmit power is directly related to node energy consumption [18], and (2) transmit power can affect network connectivity [50]. The MEDSR protocol is based on the principle that network
nodes should control transmit power to a minimum level so that network connectivity is maintained. The need for transmit power adjustment is illustrated in Figure 5.5. In that figure node n1 is transmitting packet to n2 and node n3 is transmitting packet to node n4. The transmission radii of nodes n1 and n2 are shown in that figure by dashed line. Two communications will be successful if none of those two transmissions interferes with each other as shown in Figure 5.5(a). Two unsuccessful transmissions are shown in Figure 5.5(b). In this case transmission power levels of node n1 and node n3 are too high to interfere those two communications. On the other hand, those two communications are unsuccessful as shown in Figure 5.5(c) because the transmission radii of node n1 and node n3 are too low. Hence transmit power should be as low as possible and at the same time transmit power level should maintain connectivity of the network. It has been shown that energy consumption will be minimum if transmit power is maintained at minimum level (5.2). How network connectivity can be maintained by adjusting transmit power during the route discovery is illustrated in later section where the MEDSR protocol is explained. In this section, it is shown analytically how much energy can be saved if a node adjusts its transmit power to a minimum level based on the distance between itself and the next hop.

In MANET, the transmit power of a node is usually fixed to a preset value. That transmit power does not vary with the distance between the transmitting node and the receiving node but when the distances between the two nodes is not large, the fixed power approach can be less than ideal. That’s why this section investigates how a transmission power control is employed and how much it is effective in MANET. In the investigation, it is assumed that when two nodes are close, transmitting node employs power control and transmits at lower power level. The transmit power level is adjusted so that at the receiver the received power level just exceeds a given threshold power level, $P_{th}$. That transmit power level is labeled as the minimum transmit power level, $P_{min}$, and calculated by

$$P_{min}(d) = \frac{P_{th}d^\beta}{K},$$

where $d$ is the distance between two nodes, $n$ is the path loss exponent and $K$ is a constant. Typically $\beta$ ranges between 2 and 4. In this study, $\beta$ is selected 4, which illustrates path loss exponent for two-ray ground model [56]. The typical value of $P_{th}$ for LAN 802.11 network
Figure 5.5: (a) Minimum transmit power, (b) high transmit power and (c) low transmit power
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The card is $3.653 \times 10^{-10}$ mW. Substituting the value of $P_{\text{min}}$ into (5.2), we can estimate the minimum energy consumption as

$$E_{\text{min}} = K_3(D)d^4 + K_2,$$  \hspace{1cm} (5.4)

where $K_3$ has the value of $2.8 \times 10^{-10} \mu J/\text{byte-m}^4$. It can be concluded from (5.4) that the minimum energy consumption depends on the distance between two nodes. On the other hand, for fixed transmit power, the fixed energy consumption can be expressed as

$$E_{\text{max}} = K_4(D) + K_2,$$  \hspace{1cm} (5.5)

where $K_4$ has the value of $1.62 \mu J/\text{byte}$. The detail derivation of (5.5) can be found in [18]. Hence the energy saving that can be obtained by using the minimum transmit power instead of fixed transmit power is given by

$$S(D, d) = E_{\text{max}} - E_{\text{min}}.$$  \hspace{1cm} (5.6)

Idea of minimum energy saving model can be extended in to random network scenario. In random network scenario, it is assumed that the mobile nodes are randomly distributed to the area, if coordinates of the node is given by $(x, y)$, where $x$ and $y$ are uniformly distributed random variables, between 0 to $a$, and 0 to $b$, respectively, where $a$ and $b$ are the length and the width of the area, respectively. In that scenario, it is essential to find the average link distribution between a random source-destination pair. Analysis made in [48] gives the cumulative distribution function for the distance between a random source-destination pair. That cumulative distribution function (cdf) is given by

$$P(d \leq bx) = \begin{cases} 0 & x \leq 0 \\ x^2\left(\frac{1}{2\pi_2} - \frac{8}{3\pi_2} + \pi\right) & 0 \leq x \leq 1 \\ \frac{1}{3}\sqrt{x^2 - 1} \left(2x^2 + 1\right) - \left(\frac{1}{2\pi_2} + 2x^2 - \frac{1}{3}\right) + 2x^2 & 1 \leq x \leq \sqrt{2} \\ \left[\sin^{-1}\left(\frac{1}{2}\right) - \cos^{-1}\left(\frac{1}{2}\right)\right] & x \geq \sqrt{2} \\ 1 & \end{cases},$$  \hspace{1cm} (5.7)

where $x = \frac{b}{a}$. It is straightforward to find the probability distribution function, $p(x)$ for the distance between a source and destination pair. Let us assume that for a given network
size, the expected distance between a source and distance is denoted by \( d \), and it can be found by

\[
d = \int_{x=0}^{\sqrt{d^2}} x p(x) dx
\]

If the transmission radius of the nodes is fixed (i.e., fixed transmission power), and it is given by \( R \) meters, the number of hops (i.e., links), denoted by \( H \), that a packet will travel is

\[
H = \left\lfloor \frac{d}{R} \right\rfloor,
\]

(5.8)

The total energy consumed while transmitting a packet from source to destination is expressed by

\[
E_1 = E_{\text{max}} \times H,
\]

(5.9)

where \( E_{\text{max}} \) is given by (5.5). On the other hand, if the nodes employ power control and adjust to have a transmission radius, \( r \), which is smaller than and equal to \( R \), the number of hops that a packet travel, denoted by \( h \), is given by

\[
h = \left\lfloor \frac{d}{r} \right\rfloor.
\]

(5.10)

Then the energy consumption while transmitting a packet from a source to a destination can be expressed as

\[
E_2 = \sum_{i=1}^{h} E_{\text{min},i},
\]

(5.11)
where $E_{\text{min},i}$ is the energy consumption while transmitting packet over the $i$th hop and $E_{\text{min},i}$ is given by (5.4). In order to demonstrate, effectiveness of this model, a random network scenario is created with 80 mobile nodes. Those nodes are distributed randomly over an area of $700m \times 700m$.

The energy saving that can be achieved using different transmission power is illustrated in Figure 5.6. That demonstrates that power control approach, although packets travel more hops, significant energy saving can be achieved. There are several handicaps if the selected power levels are too small. One of the handicaps is that a packet may travel a large number of hops, and this can increase delay. The other handicaps are that short transmission ranges can cause network partitioning and large number of overhead can be generated. Six different power levels are used in [50] in the route discovery phase. Hence a large number of overhead is generated in the network. In order to avoid those undesirable scenarios, in the implementation of minimum energy routing protocols two transmission ranges are selected, where one is high and the other is low. The selected two transmission power levels correspond to a transmission ranges of 125 meters and 250 meters. When a source initiates route discovery process, it will first try to use low power level to discover a route to the destination. If a source can not reach the destination with that low power level after certain attempts, it will raise the transmit power level to a high level. Once a source discovers a route using any of those power levels, each hop further adjusts transmit power based on the distances between two neighboring hops.

### 5.4 MEDSR protocol

Minimum Energy Dynamic Source Routing (MEDSR) protocol is enhanced form of the DSR protocol. The enhancements are made to DSR route discovery mechanism to allow energy aware and efficient operation. The MEDSR protocol consists of two basic mechanisms: two power level route discovery and link-by-link power adjustment. Route request packet is used to discover a route that is more energy efficient and route reply packet is used to adjust transmit power link-by-link. The route discovery mechanism in the MEDSR protocol uses several power levels in the route discovery process. The nodes try to obtain a route to the
destination by initially transmitting low power levels, if they are not successful at this low level, they increase their transmit power and try again. This process continues until one of the tried power level returns a successful discovery. In the implementation phase, two power levels are tried, one is low and the other one is high. The low power level allows nodes to reach up to 125 meters, and the high power level allows to 250 meters. A sample scenario for this implementation is illustrated in Figure 5.7 (a) and Figure 5.7 (b).

5.4.1 Route discovery

The route discovery process of MEDSR protocol using low power level is depicted in Figure 5.7 (a), where the source node $S$ has some packet to send to the destination node $D$. Then, node $S$ initiates a route discovery process by broadcasting a request message at low power level (i.e., range of 125 meter). The route request packet of DSR protocol has been modified to carry power level information in the packet header. When the next hop node $A$ receives the request packet, it determines whether it is the destination or not. Since $A$ is not the destination, it adds its address to the request packet and forwards the request packet to its neighbor at the same power level at which it received packet from source $S$. This process goes on until the request packet reaches the destination node $D$. After receiving the request message, the destination node $D$ replies back after copying the routing information accumulated in the request packet into the route reply packet. The route reply packet of
DSR has also been modified to carry power level information, and that field has the copy of the power level information contained in the request packet. When the destination node \( D \) replies back to source node \( S \), the next hop \( C \) receives that route reply packet. Suppose node \( C \) receives that reply packet, and measures the received power level, \( P_{\text{recv}} \), since the route reply packet contains the the transmit power level information, \( P_{\text{tx}} \), of node \( D \). Node \( C \) can estimate the required minimum transmit power to reach node \( D \) by taking the difference. That is

\[
P_{\text{min}} = P_{\text{tx}} - P_{\text{recv}} + P_{\text{th}},
\]

where all the values are in dBW. \( P_{\text{th}} \) is the threshold power level for successful packet reception (i.e., receiver sensitivity). The typical value of \( P_{\text{th}} \) is \( 3.652 \times 10^{-10} \) watt. In order to avoid unstable links due to channel randomness, a safety power level margin, \( P_{\text{margin}} \), in dBW, is added to \( P_{\text{min}} \). Finally \( P_{\text{min}} \) is given by

\[
P_{\text{min}} = P_{\text{tx}} - P_{\text{recv}} + P_{\text{th}} + P_{\text{margin}}.
\]

In the implementation, safety margin is set to 3.0 dB, which was suggested in [18] as well. After that adjustments, node \( C \) determines the required transmit power to reach node \( D \), and it stores this minimum transmit power in a table called power table as shown in Figure 5.7 (a). Each entry in the power table has two values: (1) next hop's id and (2) the minimum transmit power for that next hop, which is determined by (5.13). For example, the intermediate node \( C \) will store the id of the destination \( D \) and the minimum transmit power to reach that node in the power table. Node \( C \) then forwards that route reply to next hop \( B \). Node \( B \) determines the minimum transmit power as mentioned before and store the minimum transmit power in the power table for node \( C \). Node \( A \) and node \( S \) also repeats the same procedure. When the source \( S \) receives the route reply packet, it stores the route in the route cache and starts transmitting packets using that route. While transmitting packets, each node uses its power table to determine the minimum transmit power to reach the next hop along the route and uses this power level to forward the packet to the next hop. In that scenario, since the link distances between two nodes are less than 125 meters, the source node is able to discover the route.
But there are some cases where a source can not discover a route at the low transmit power level as illustrated in Figure 5.7 (b). In that case, the source node switches to a high power level route discovery. In the Figure 5.7 (b), the distances between nodes are 220 meter. In this case, source node $S$ can not discover the route by using low transmit power level since the distance between node $S$ and the next hop is larger than 125 meters. In order to ensure finding routes to the destination, the source node will increase the power level to high (i.e., transmission radius of 250 meters) after certain number of unsuccessful attempts. In the implementation, three unsuccessful attempts triggers the switch from low to high power level. In other words, in the MEDSR protocol, if a source can not find a route by sending 3 route request packets, it assumes that it can not reach the destination with low power level, and then it will attempts to find a route with high power level. Once routes are discovered with high power level, the process of handling route request is similar to that of low power level. The only difference is all nodes forward request packets at high power level. Once route request packet reaches the destination $D$, it sends reply back to the source. The route reply packet is used to adjust transmit power link-by-link as mentioned in above. If node can not find a route to destination at high power level after 3 attempts, it declares that this destination is unreachable.

5.5 Performance analysis of MEDSR protocol

MEDSR protocol is implemented and tested by NS-2 to verify its viability and correctness of the operation. After this implementation, different scenarios are tested to compare MEDSR with DSR. In those scenarios, twenty pairs of UDP connections with constant bit rate (CBR) traffic were used to test the performance. The packet generation rate was 1 packet/sec. Each CBR traffic started at random time during the simulation period. The performance of MEDSR protocol was tested with two different types of energy constraints: (1) mobile nodes were assigned a large amount of energy and the simulations were run for a limited period of time, and (2) mobile nodes were assigned a limited initial energy and the simulations were run for a long period of time.
5.5.1 Case I

In the first case, a large initial energy were assigned and the simulations were run for a limited time. The reason of this case was to ensure no node exhausted its battery during the simulation time, which eliminated route breakage during the simulations. Thus the connectivity of the network was maintained throughout the simulation. Hundreds nodes were randomly distributed in an area of $500m \times 500m$. Then, by keeping the same number of nodes and connections, the network area was increased to $1000m \times 1000m$, $1250m \times 1250m$ and $1500m \times 1500m$. The initial energy was set to 200 Joules at each node. Each simulation was run for 250 seconds. Ten different topologies were generated for a given network size and the results shown here are the average of all those ten simulations. The total energy consumption $E_{total}$ contains the energy consumption by all types of packets at the end of simulation. Another parameter that is observed was the number of packets, $n$, delivered to the destination. The energy consumption per data packet is the ratio of $E_{total}$ and $n$. The energy spent per data packet for DSR protocol and MEDSR protocol are shown in Figure 5.8. In case of DSR protocol, investigating this figure demonstrates that the energy consumption per data packet is 1.8 mJ when the network area is $500m \times 500m$ and 6.0 mJ when the network size is $1500m \times 1500m$ for fixed transmit power. On the other hand, those energy consumptions are 0.8 mJ and 4.0 mJ for similar network area. It can be concluded that the energy consumption per data packet increases in both DSR protocol and MEDSR protocol as the network size increases because the distance between the nodes increases, and eventually low power levels in MEDSR does not return routes with this power level, and MEDSR and DSR virtually operate on same routes. The advantage of using MEDSR is more evident in dense networks. The energy saving is maximum when the network is more dense where up to 50% energy saving is possible in $500m \times 500m$ area. That saving decreases with increasing network size. When the network size is $1500m \times 1500m$, the energy saving provided with MEDSR protocol is nearly 30%.
5. **HIERARCHICAL MINIMUM ENERGY DSR (HMEDSR) PROTOCOL**

5.5.2 Case II

In the second case, 100 nodes were randomly placed in an area of 2000m × 2000m. The data traffic model and other parameters are as same as in the previous case, but a limited initial energy of 20 Joules was assigned to each mobile node. The simulations are run for 5000 seconds. In those scenarios, the packet transmission stops at certain point in the simulation when links were broken because of battery exhaustion in the nodes. Those experiments show how many data packets could be sent successfully to the destination by a particular network when the mobile nodes have limited energy resources. The simulations results of those experiments are shown in Figure 5.9.

That figure demonstrates there is a potential to save up to 53 % with MEDSR. When the network size is the smallest which is 2000m × 2000m, almost 40 % more data packets were delivered to the destination by using the MEDSR protocol. When the network gets larger, the number of data packet delivered of MEDSR protocol and DSR protocol becomes similar because the average link distance between nodes increases with increasing network size and this reduces potential energy saving in MEDSR. If the network size increased further, the link distances become similar in both protocols. That is why similar number of data packets are delivered to the destinations in both DSR and MEDSR protocols.

From the simulation results, that energy consumption per data packet can be reduced, that can lead to delivery of more data packets if MEDSR protocol is employed. When energy consumed per packet is considered, the energy consumed by transmission of data packets, as well as MAC packets and routing control packets are included. From the simulation studies, it is discovered that when the number of nodes in the network gets larger, the energy consumed while transmitting MAC packets and routing control packets exceeds the energy consumed while transmitting data packets.

That leads to conclusion that to have energy efficient routing, there is a need to reduce the routing control packets and MAC packets (i.e., overhead packets) in the network. That’s why reducing overhead in the network becomes essential to provide scalability and further efficiency to MEDSR. Hierarchicy is one of the ways that can reduce the control overhead and proportionally the MAC overhead. Hierarchical Dynamic Source Routing (HDSR)
Figure 5.8: Energy consumption per data packet in DSR and MEDSR

Figure 5.9: Data packet delivered to destination in DSR and MEDSR
introduced in [67] and discussed in Section 3.2 can be modified and combined to improve the energy efficiency of MEDSR in large networks. The next section will introduce a new protocol, called Hierarchical Minimum Energy DSR (HMEDSR), that is based on HDSR in the following section.

5.6 Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) Protocol

The main objective of HMEDSR is to reduce the overhead packets, routing control and MAC packets, in MEDSR. HDSR protocol and the MEDSR protocol have their own advantages. In HDSR protocol, the number of overhead packets is reduced significantly. Hence a node spends less energy in transmitting overhead packet and node will have more remaining energy in transmitting useful data packet. On the other hand, the MEDSR protocol saves energy while transmitting data packet. That is why HMEDSR protocol is a combination of both the HDSR protocol and the MEDSR protocol. That is, a source node initiates a route discovery protocol, first with low power level if this unsuccessful, with high power level just like in the MEDSR protocol. But how those route discovery packets handled by neighboring
5. HIERARCHICAL MINIMUM ENERGY DSR (HMEDSR) PROTOCOL

Figure 5.11: Energy consumption comparison of DSR and HMEDSR protocols

<table>
<thead>
<tr>
<th>Node</th>
<th>DSR (mJ)/pkt</th>
<th>HMEDSR (mJ)/pkt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data</td>
<td>MAC</td>
</tr>
<tr>
<td>100</td>
<td>2.45</td>
<td>1.05</td>
</tr>
<tr>
<td>200</td>
<td>3.90</td>
<td>1.76</td>
</tr>
<tr>
<td>300</td>
<td>5.3</td>
<td>2.11</td>
</tr>
</tbody>
</table>

Figure 5.12: Energy consumption comparison of DSR and HMEDSR protocols

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nodes is different. In HMEDSR, after receiving a request packet, an intermediate node initiates a forwarding node selection mechanism. In that mechanism, the node goes into back-off time as in HDSR protocol as oppose to immediately transmitting the request packet immediately as in MEDSR protocol. That back-off time is given by (5.14). The back-off time is determined by a uniform random variable $R$, initial energy $E_{\text{initial}}$, residue energy $E_{\text{current}}$ and scaling factor $K$. When $E_{\text{initial}}$ and $E_{\text{current}}$ are almost equal, the back-off time solely depends on the $R$ and $K$. The value of $R$ is in the range of 0-1.0. We set the value of $K$ to 5.0 such that when a node is almost out of battery energy, the maximum back-off time will be equal to 10.0. But that back-off time will be less for those nodes which have high energy level. Hence nodes which have high energies are more likely to become forwarding nodes and are more likely to participate in the network operation. Thus the overall network life-time is maximized by minimizing the number of 'dead' nodes in the network.

Among the nodes whose back-off time is the lowest will time out first, then this node will re-broadcast the request packet first. The nodes that are still in the back-off phase, will hear this communication and they stop their timers, and save the remaining time period for future use. This process continues until a route is found to the destination. But if a route discovery fails to return a route, then source initiates a new route discovery, and at this time nodes that did not broadcast the request packets previously, broadcast the request according to how much time left in their timers.

$$T = \left(R + \left(1 - \frac{E_{\text{current}}}{E_{\text{initial}}} \right) \right) \times K,$$

(5.14)

When a destination node received the route requests, it replies back, and link-by-link transmit powers are adjusted to a minimum level, and power tables are constructed at each node as explained in MEDSR.

### 5.6.1 Simulation results

In order to investigate the energy consumption in HMEDSR protocol and compare the results with that of DSR protocol, the simulation model and scenarios explained in Section 5.2
5. HIERARCHICAL MINIMUM ENERGY DSR (HMEDSR) PROTOCOL

![Graph](image)

Figure 5.13: No. of data pkt. delivered with initial energy for 25 Joules

![Bar Chart](image)

Figure 5.14: Comparison of energy consumption by DSR, MEDSR and HMEDSR protocols

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is repeated for HMEDSR in NS-2. Some of the results are presented to show if HMEDSR is indeed providing improvement over DSR. The simulation results are presented in Figures 5.12. Figure 5.12 shows the energy consumption while transmitting data packet, MAC packet and routing packet. In those simulations, total energy consumed by different types of packets and the total number of data packets were measured at the end of simulation. The energy consumed per data packet is measured by ratio of the total energy consumed and the total number of data packets delivered to the destination. It is shown in Figure 5.11 and Figure 5.12 that in DSR protocol, the energy consumptions by data packet are 2.45 mJ, 3.90 mJ and 5.3 mJ when network sizes are 100 nodes, 200 nodes and 300 nodes. On the other hand, those energy consumptions are 1.5 mJ, 2.2 mJ and 3.30 mJ when HMEDSR protocol is used. There is not significant difference in the energy consumption by MAC packets. But the energy consumption by routing packet is huge. When DSR protocol is used, routing energy consumptions per data packet are 0.11 mJ, 0.36 mJ and 1.1 mJ when network sizes are 100 nodes, 200 nodes and 300 nodes. On the other hand, those routing energy consumptions are 0.033 mJ, 0.09 mJ and 0.20 mJ when HMEDSR protocol is used. Hence almost 70%, 75% and 82% of routing energy can be saved by using HMEDSR protocol. That saving in routing energy is reflected into the total energy consumption. The total energy per packet in transmitting different types of packets are 3.61 mJ, 6.02 mJ and 8.51 mJ when network size is 100 nodes, 200 nodes and 300 nodes respectively and DSR protocol is used. On the other hand, those energy consumptions are 2.73 mJ, 3.98 mJ and 5.71 mJ. Hence around 25% of energy is saved for small network of 100 nodes and almost 30% energy is saved for large network of 300 nodes. When DSR protocol is used, the major portion of energies of nodes is consumed by data packet for network size of 100 nodes. But as the network gets larger, the major portion of energy is consumed by overhead packets. So it can be concluded that nodes' energies are used more efficiently in HMEDSR protocol compared to DSR protocol. From Figure 5.11, it is clearly depicted that there is always a saving in energy when HMEDSR protocol is used. But the difference in energy saving is more when network size is larger.

In order to test how that kind of energy saving can affect the network life-time when
HMEDSR protocol is used, an initial energies of the of 25 Joules was assigned to each node. The simulations were run for 5000 seconds to ensure that nodes die out and no node transmits data packet any more. The number of data packet sent to destination successfully is shown in Figure 5.13. From that figure, it can be concluded that the number of data packet was successfully delivered to the destination in DSR protocol is 4008. But in HMEDSR protocol, that number is 9883. That means almost 90% more packet was sent to the destination in HMEDSR compared to DSR protocol. Similarly, 80% more packets were sent to destination when network size is 200 nodes and 90% more packets were delivered to destination when network size is 300 nodes.

5.7 Conclusion

In this paper, two new protocols Minimum Energy Dynamic Source Routing (MEDSR) and Hierarchical (MEDSR) are proposed, and their performances are investigated via computer simulations. Although MEDSR improves energy efficiency and network life-time of the network, especially in the dense networks. But the energy efficiency drops with increasing network size because of transmitting routing overhead packets and MAC layer packets in addition to data packets. Considerable portion of total energy is dissipated by overhead packets. In order to limit, and improve the MEDSR, HMEDSR is introduced. HMEDSR protocol effectively eliminates unnecessary overhead packets, and considerably improves the performance of MEDSR. Both HMEDSR and MEDSR provides order of magnitude energy efficient operation in MANET than DSR which is illustrated in Figure 5.14. From that figure, it is shown that the total energy consumption by different types of packets is always less in MEDSR protocol. That energy saving increases with the network size. Since overhead of MEDSR protocol has been further reduced by using HMEDSR, more energy saving is achieved by using HMEDSR protocol.
Chapter 6

Cross-layer based Multipath HDSR (CMHDSR) protocol

6.1 Multipath routing for ad hoc network

In reactive routing protocols like Dynamic Source Routing (DSR) [10] protocol and Ad hoc On-demand Distance Vector (AODV) [54] use the shortest hop algorithm to make routing decision. Once all paths are discovered, a source node chooses a path, which minimizes a predefined path cost (e.g., shortest path, minimum energy or delay path). Studies in [4, 9, 55] and [74] show that the shortest path algorithm is not a good choice for MANET. When the shortest path algorithm is used, nodes located around the center of the network carry more traffic compared those located at the perimeter of the network. When a number of connections are set up in the network, the wireless links lying around the center of the network carry more traffic and hence get congested, which may affect the performance of the network in terms of delay, life-time and throughput. In mobility scenarios, the shortest path may break due to node movement. Moreover, communication through wireless medium is unreliable, and is also subjected to link errors, especially when MANET is deployed in a hostile environment. This is the reason that the shortest path routing may cause
an increase in the link error probability. To overcome limitations of the shortest path routing protocols, researchers have suggested multipath routing instead. Multipath routing protocols proposed for MANET can be broadly classified as (a) delay-aware multipath routing protocols, (b) reliable multipath routing protocols, (c) minimum overhead multipath routing protocols, (d) energy efficient multipath routing protocols and (e) hybrid multipath routing protocols. Delay-aware multipath routing protocols, proposed in [12, 29, 32, 43] and [45], choose multiple paths so that overall delay performance of a network is improved. Reliable multipath routing protocols, proposed in [11, 41, 47, 74, 75, 77, 81] and [84] support reliable data transfer between source and destination. Minimum overhead multipath routing protocols, proposed in [3, 39, 49, 51, 79, 85] and [88], discover and use multiple paths by using minimum overhead control messages. Energy efficient multipath routing protocols as proposed in [19] and [42], maximize life-time of a network by using energy efficient path selection. Hybrid multipath routing protocols proposed in [76] and [78], use both the shortest path and multipath algorithms in routing protocols. Although each multipath routing protocol has its own unique advantages and disadvantages, they have some design issues in common such as: (1) how to discover multiple paths, (2) how to select those paths, and (3) how to distribute load among those paths. To address these issues most of the multipath routing protocols modify either DSR or AODV protocol. The taxonomy of the multipath routing protocols is depicted in Figure 6.1. Split Multipath Routing (SMR) [39], Multipath Source Routing [76], Robust Multipath Source Routing (RMPSR) [78], Cluster based Multipath Dynamic Source Routing (CMDSR) [3] and Disjoint Multipath Source Routing (DMPSR) [79] have all been designed by modifying DSR protocol. On the other hand, Node Disjoint-Multipath Routing (NDMR) [41], Multipath AODV (AODVM) [85], Multipath AODV with Path Diversity (AODVM/PD) [49], Multipath AODV with Path Selection (AODVM-PSP) [32] and Split-N-Save Multipath Routing [12] have been designed by modifying AODV protocol.
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6.2 Issues and challenges in designing multipath routing protocols

To improve Quality of Service (QoS), reliability and energy efficiency of MANET, multipath routing protocols have been used. While designing these protocols, researchers mainly address three major fundamental issues:

- How to discover multiple paths- To discover multiple paths from a source to a destination, the basic route discovery mechanisms used in DSR and AODV protocols, need to be modified. In fact, one of the major reason for using multipath routing is to discover multiple paths that should be ‘node-disjointed’ or ‘link-disjointed’. In the node-disjointed paths, nodes on the paths should not be common. In the link-disjointed paths, links on the paths should not be common. Route discovery mechanisms commonly used in MANET are modified so that maximum number of node-disjoint or link-disjoint paths are discovered. Once all node-disjoint or link-disjoint paths have been discovered, there arise other issues such as how to select suitable paths from all discovered paths and what node should do that selection namely the source or the destination node.
6. CROSS-LAYER BASED MULTIPATH HDSR (CMHDSR) PROTOCOL

- How to select path- Once multiple paths have been discovered, a multipath routing protocol should decide how to select multiple paths for transmitting data packet. If a number of paths are discovered, how many of those paths should be used; i.e. only a few [39] or all of them [74]. If only a few paths are used, performance of multipath routing protocol should be similar to that of a shortest path routing protocol. On the other hand, if all paths are used, there may be chance of selecting excessive long paths, which may adversely affect the performance of multipath routing.

- How to distribute load- Once a path or a set of paths have been selected, a good multipath routing protocol should decide how to use these multiple paths while transmitting packets; i.e. transmit packet by using all of those paths in round-robin fashion [77], or use the paths at random or use a path for transmitting a preset number of packets [12] and then use a different path to transmit the same preset number of packets or distribute packets depending upon the reliability or the delay of a path. Another issue is how a source node should send packets; i.e. should it divides a packet into multiple segments and sends those segments by using different paths or should it send duplicate copies of a packet using different paths.

Although multipath routing protocols provide improved load distribution, reliability, delay and energy efficiency, they also have some disadvantages. Some of the disadvantages are:

- Longer paths- In multipath routing protocol packets usually travel for longer hops. That is why packet may suffer larger delay compared to the shortest path routing. To avoid using excessively longer paths, multipath routing protocols usually do not use all discovered paths. Instead, they only use a selected number of paths. As for example, Split Multipath Routing (SMR) proposed in [39] uses two paths, one is the shortest path and the other path which is maximally disjointed with the shortest path. Two paths are considered maximally disjointed when they have the least number of common node.

- Special control message- Multipath routing protocols cause some additional control messages in addition to basic route discovery and route maintenance control messages.
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The additional control messages are used by the network nodes while collecting information about neighboring nodes so that suitable paths (node disjointed or link disjointed paths) are discovered. As for an example 'beacon' message is used in [84] to create neighbor table. 'Hello' message is used in [3] to form hierarchy among network nodes. The special messages used in multipath routing can overwhelm the network, especially when the network size is large. Those messages can occupy a significant portion of bandwidth and hence can adversely affect the network performance.

- Route request storm- Multipath routing protocols can generate route request 'storming' in MANET. In multipath routing protocols proposed in [39], [49] and [85], intermediate nodes are not allowed to discard duplicate request messages as in DSR or AODV protocols. Instead, the nodes forward that duplicate request messages, which can cause a huge number of redundant overhead packets in the network.

- Inefficient route discovery- Multipath routing protocol may use inefficient route discovery process. For example, in the route discovery processes of DSR or AODV protocol, intermediate nodes are allowed to send reply from their caches to the source if they have any suitable route in their route caches for the destination. This route reply helps the source node to find route to a destination in shorter period of time because a source node does not wait until the request packet reaches to the destination and destination node replies to source. To find node-disjoint or link-disjoint paths, multipath routing protocols proposed in [49] and [85] prevent intermediate nodes to send replies even if they have some routes in their route caches. Thus a source should wait until the destination replies back. Hence route discovery time in multipath routing protocol is higher compared to route discovery time in DSR or AODV protocols.

- Duplicate packet processing- To ensure reliable data transfer, multipath routing protocols, proposed in [74] and [77], send duplicate packets using different paths. Duplicate packets create redundant packets and hence occupy a large bandwidth. Moreover, to generate duplicate packets in the source and to filter out these duplicate packets in the destination, special arrangements need to be made. For example, in multipath
routing protocol proposed in [77], two agents called 'Duplicate Packet Agent (DPA)' and 'Duplicate Packet Filter (DPF)' are used for generating duplicate packets and for filtering duplicate packets, respectively. To filter out the redundant packets, network layer needs to include 'Duplicate Packet Filter' at the destination node. Similarly, 'Duplicate Packet Agent' is required at the source to produce duplicate packets from the original packet.

### 6.3 Multipath version of DSR and HDSR protocols

In this chapter, new protocols called Multipath Dynamic Source Routing (MDSR) protocol and Cross layer based Multipath Hierarchical Dynamic Source Routing (CMHDSR) are proposed. MDSR protocol is originated from DSR protocol. A cross layer elements have been used to implement MDSR protocol. In MDSR protocol, the congestion information at the MAC layer has been used in the network layer. Depending upon the congestion level, a mobile node decides whether to forward a route request or not to forward that route request. If the congestion level of a node is above some threshold value, a mobile node discards a request packet; otherwise it should forward that request packet. Hence less congested nodes are selected in routing. It is shown via simulations that network performances in terms of end-to-end delay and network throughput are improved in MDSR protocol compared to DSR protocol. Obviously MDSR protocol reduces overhead packets generated in the network by dropping request packet based on congestion levels of the nodes. The number of overhead is further reduced by a protocol called Cross layer based Hierarchical Multipath Dynamic Source Routing (CMHDSR) protocol. To implement CMHDSR protocol, the MDSR protocol has been combined with the Hierarchical Dynamic Source Routing (HDSR) protocol (which was explained in chapter 3). It has been mentioned in Chapter 3 that HDSR protocol classifies network nodes into Mobile Node (MN) and Forwarding Node (FN). FNs are selected by an FN selection algorithm. Medium Access Control (MAC) layer congestion information is used in the FN selection algorithm. By doing that, the probabilities of discovering routes that are located in the less congested areas of the network are increased. Thus, HDSR protocol improves the routing performance. But HDSR protocol has some
6. CROSS-LAYER BASED MULTIPATH HDSR (CMHDSR) PROTOCOL

limitations too. When an MN becomes FN, it continues forwarding packet for other nodes and it may become congested eventually. To avoid this problem, in CMHDSR protocol, a limit has been set up on the traffic carrying capacity of FN. An FN should stop carrying traffic for other nodes if that FN becomes congested. Hence there will be a new set of FNs created in the network and network traffic will be redistributed among those new FNs. The simulation results shows that CMHSR protocol improves the performance of HDSR protocol in terms of end-to-end delay and network throughput.

6.4 Multipath Dynamic Source Routing Protocol (MDSR) protocol

The DSR protocol has been modified to implement MDSR protocol. In DSR protocol, a source may discover multiple paths to the destination node by using the route discovery mechanism. Once paths are discovered, a source node uses the shortest path to send data packets to that destination. But the shortest path may not be a good choice. The major problems of shortest path routing are (1) unfair load distribution, (2) congestion, (3) contention and (4) collisions. Those problems are illustrated with respect to the scenario of Figure 6.2. In that figure, there are two on going communications along the paths $X - A - B - U$ and $Y - A - B - V$ when the source $Z$ initiates a discovery mechanism to find a path to its destination, $W$. From that route discovery, two paths $Z - A - B - W$ and $Z - C - D - E - W$ are found. If the shortest path is chosen, the source $Z$ will use the route $Z - A - B - W$. But when the source $Z$ sends data packets along the path $Z - A - B - W$, the nodes $A$ and $B$ will be over utilized. Hence those nodes will exhaust battery very soon. On the other hand, nodes $C$, $D$ and $E$ are under utilized. Moreover, the link $A - B$ will be congested and packets along the link $A - B$ will experience delay. The new connection also affects the existing connections. For the scenario of Figure 6.2, the number of transmitting nodes in a region (marked as shaded) will increase when node $Z$ starts transmitting packets and more nodes will contend for the medium in that shaded region. Because in an typical MAC layer mechanism like IEEE 802.11, only one node in a
given region can transmit packet at a time. For example, when node $Z$ transmits or node $A$ forwards node $Z$’s packet, other nodes $X$ and $Y$ can not transmit. Hence the traffic carrying capacity of that region is affected by the new connection. When the number of node in given region increases, the collision probability also increases for that region. Although the collision probability has been minimized in IEEE 802.11 by adopting a collision avoidance mechanism, but there is still chance of having packet collision. That collision probability for IEEE 802.11 MAC layer has been formulated in [4], which is given by

$$\gamma = 1 - e^{-(n-1)\alpha} \quad (6.1)$$

where $n$ is the number of neighbors in a given region, $\alpha$ is the parameter of the exponential back-off duration, thus $\frac{1}{\alpha}$ has units of time. For the given region of Figure 6.2, the number of transmitting node $n$ increases from 3 to 4 when the new connection is set up in that region. Hence collision probability for that region will increase too. Those problems related to the shortest hop algorithm becomes more severe when there are multiple connections operating simultaneously in the network. It is shown in [55] that nodes located around the center of the network carry more traffic compared to the nodes located far from the center of the network. [12, 29, 32, 43] and [45] shows that multipath routing should not only ensure load distribution in the network, but it should also distribute load in such a way so that congested portions are avoided while making routing decision. Motivated by those works, a new protocol called Multipath Dynamic Source Routing (MDSR) has been proposed in this chapter. In MDSR protocol, network traffics are distributed among nodes. For the scenario mentioned in Figure 6.2, traffic load on node $A$ and $B$ can be reduced if the traffic of node $Z$ is diverted to the other paths, which is marked as $Z - C - D - E - W$. To do that node $A$ should not re-broadcast the request packet issues by source $Z$. When node $A$ drops the request of source $Z$, the route $Z - C - D - E - W$ will be discovered. That route will be used by source $Z$ to send packet to the destination $W$. The modified network topology has the following advantages (1) the traffic load on node $A$ and $B$ will be reduced, (2) reduced number of nodes in the shaded region will contend for the medium and hence capacity of that region will increase and (3) there will less number of collisions in the shaded region. Hence there will less number of packet loss. To determine when to drop a request packet, a
6. CROSS-LAYER BASED MULTIPATH HDSR (CMHDSR) PROTOCOL

Cross layer design is adopted in the routing protocol. The congestion information available at the MAC layer is used in the network layer to decide when node A (Figure 6.2) should drop the request packet of source Z. IEEE 802.11 has been used as MAC layer protocol. A typical medium access mechanism of IEEE 802.11 MAC layer is shown in Figure 6.3.

The IEEE 802.11 uses a Distributed Coordination Function (DCF) access method to support asynchronous data transfer among a set of mobile nodes. The DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). There are two types of carrier sensing mechanisms used in IEEE 802.11 (1) physical carrier sensing and (2) virtual carrier sensing. By physical carrier sensing, a mobile node detects the presence of other mobile node within the transmission region by monitoring the surrounding traffic. On the other hand, virtual carrier sensing in implemented in MAC layer. Mobile nodes perform virtual carrier sensing by sending the duration of packet in the packet header.

According to IEEE 802.11 medium access mechanism, when a source node has some packet to send to the destination, it monitors the medium for a period of time called Distributed Inter Frame Space (DIFS). If the medium is free for that period, the source node transmits the packet. When the destination node receives that packet, it also wait...
a short period of time called Short Inter Frame Space (SIFS). If the medium is free for that SIFS period, that destination node sends an acknowledgment to the source. Hence a successful communication between a source and a destination takes place for a period of time consisting of the duration of a data transmission, SIFS period and the duration of the acknowledgment transmission. The source node records that duration time in the packet header of data packet. When other neighboring nodes of the source detects the transmission of data packet, those neighbors defer their access for the medium for a period of time, which is called Network Allocation Vector (NAV). NAV indicates the amount of time that must elapses until the current transmission between source and destination will complete. After the NAV the neighboring nodes monitor channel again to determine whether the channel is idle or not. If the channel is idle for a DIFS period, those neighboring nodes back off for a random period of time. During the back off period, each node sets a timer for a random period of time. During the back off period, those nodes monitor the medium, if the medium becomes busy during the back off period, nodes freezes the timer. On the other hand, if the medium is free during that back off period, node decrements the time. When the timer of a node expires, that node monitors the channel for DIFS period again. If that node senses that the medium is free for that DIFS period, it transmits packets. But if the medium is found busy during that DIFS period, that node goes into longer back of period.
At first transmission attempt, $CW = CW_{\text{min}}$ and then it is doubled at each retransmission attempt up to $CW_{\text{max}}$. In the current version $CW_{\text{min}} = 32$ and $CW_{\text{max}} = 1024$. Thus the contention period is increased depending upon the traffic intensity of the surrounding medium. Hence the size of contention window indicates how a node is busy. That contention window is used in MDSR protocol. In MDSR protocol, when a node receives a route request packet from a source, it decides whether to forward that request or not depending upon the contention level. If the contention window becomes greater than a threshold value, a node should drop the request packet. Otherwise, it should forwards that request packet. In all simulations presented in this chapter, a threshold value of 256 has been for the contention window. That threshold value is called $CW_{\text{th}}$. The major advantages of that kind of dropping request packet based on $CW_{\text{th}}$ are: (1) overhead packet generated in the network is reduced. Hence network bandwidth is efficiently used, and (2) congested nodes are prevented from participating in network operation. Hence there it is suspected that there will be less congestion in the network. Once a set of paths are discovered, a source node selects the path, which has the shortest hop.

6.5 Performance evaluation

To test the performances of original DSR with MDSR in a more complex scenario, a network topology was created in Network Simulator (NS-2) consisting of 100 mobile nodes located randomly over the area of $1000m \times 500m$. Twenty UDP connections were set up randomly in the network. Each connection started independently and sends packet within random period of time. Each simulation was run for 250 seconds. Five different topologies were created to increase the accuracy of the simulation results and the data collected from those five simulations were averaged while reporting. The Constant Bit Rate (CBR) traffic generator was used to generate the packet. Each CBR started at different random time, and once it started, it continued generating packet till the end of the simulation. The packet generation rate was 8 packets per second. The network size was increased by keeping the node density per unit area constant. That means there are 200 nodes when the network size is $1000m \times 1000m$ and there are 300 nodes when the network size is $1500m \times 1000m$. 

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Figure 6.4: Overhead comparison of DSR protocol and MDSR protocol

Figure 6.5: Delay comparison of DSR protocol and MDSR protocol
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The overhead per data packet delivered to the destination is shown in Figure 6.4. In DSR protocol, there are 1.4, 11.0 and 36 overhead packets generated in the network when network sizes are 100 node, 200 nodes and 300 nodes. On the other hand, there are 1.6, 5.8 and 18.66 overhead packets are generated in the network when MDSR protocol is used. Those overhead reductions show that a considerable portions of overhead can be saved for large network. Figure 6.4 shows that there are reductions of 40% and 50% of overhead in MDSR protocol compared to DSR protocol. Those reductions in overhead packet were caused by dropping request packet in MDSR protocol. For small network size, network is not congested and hence the number of dropped request packet is not significant. On the other hand when the network gets larger, the congestion level is increased in the network and more packets are dropped. The delay improvement is depicted in Figure 6.5. The delays per packet are 7.0, 11.3 and 14.0 second in DSR protocol, but those delays are 7.4, 8.5 and 11 second in MDSR protocol. Those delay improvement is the results of two main reasons:

Figure 6.6: Throughput performance comparison of DSR protocol and MDSR protocol
6. CROSS-LAYER BASED MULTIPATH HDR (CMHDR) PROTOCOL

- There is less number of overhead in the network in MDSR protocol compared to DSR protocol. Hence network resource like bandwidth is used more efficiently for transmitting data packet and

- High congested nodes are avoided in the route discovery process. Hence routes located in the less congested area are discovered and used.

Those kinds of overhead reduction and delay improvement are reflected in Figure 6.6. That figure compares the data packet delivered to the destinations for DSR protocol and MDSR protocol. It is depicted in that figure that the number of data packet delivered to the destination is 9306, 8025 and 6445 for MDSR protocol; whereas those numbers are 9225, 5994 and 4542 for DSR protocol. That means there are throughput improvements of 30% and 40% when network sizes are 200 nodes and 300 nodes. But when the network size is the smallest, the throughput improvement is not significant.

In order to investigate how network behaves under different network traffic load, a network topology consisting of 200 nodes was created. The simulation parameters are similar to that mentioned in the previous simulations. But the packet generation rate was varied in this simulation. The throughput performance of the previous simulation is shown in Figure 6.7 that MDSR has better performance in terms of throughput. With DSR protocol, the network can support until 6 packets per second. Then the performance of DSR degrades when more traffic is offered. On the other hand, when MDSR is used, the network can support more traffic compared to DSR protocol. Unlike DSR protocol, the throughput of network does not decrease with increasing traffic load. Throughput improvement up to 30% is achieved at packet generation rate of 8.0 packets per second.

Although MDSR shows better performance compared to DSR, there is still excessive control overhead in both protocols; because both protocols use flooding to discover routes to the destination. flooding generates a large number of overhead packets in the network and those overhead packets consume a large portion of valuable bandwidth. Flooding deteriorates the performance of large networks. It is shown in Figure 6.4 that the routing overhead increases with the network size. To reduce that flooding effect and to take advantages of multipath path routing, Cross Layer based Multipath Hierarchical Dynamic Source
Routing (CMHDSR) has been proposed in this chapter. In CMHDSR protocol, the MDSR protocol has been combined with HDSR protocol. There are two advantages of CMHDSR protocol. These are:

- Overhead packets generated by MDSR protocol is reduced significantly by using a hierarchical design
- Fair load distribution is ensured among forwarding nodes of HDSR protocol.

### 6.6 CMHDSR protocol

Cross Layer based Multipath Hierarchical Dynamic Source Routing (CMHDSR) intents to reduce unnecessary overhead in the network by using a hierarchical algorithm. Thus flooding in the network is reduced during the route discovery phase of the network. In addition to hierarchy, a cross layer approach is employed such that only the nodes lying along less congested areas of the network participate in the route discovery mechanism. The
CMHDSR protocol generates hierarchy among network nodes and hence reduce overhead generated during route discovery. The route discovery mechanism of DSR protocol has been modified to implement CMHDSR protocol. According to the modified route discovery mechanism, a node handles route request packet depending upon the status of a node. Network nodes can be in two states: Regular or Forwarding state. When a node is in regular state, it is called Mobile Node (MN) and when a node is in forwarding state, it is called Forwarding Node (FN). Initially all network nodes are in MN state. The route discovery mechanism of CMHDSR protocol works as follows.

If a node is either in MN state and it receives a request packet, that node first checks its contention level. If the contention level is already greater than $CW_{threshold}$, that node should drop the request packet. But if the contention level is less than $CW_{threshold}$ and a node is in MN state, that node goes into a back-off time. That back-off time is proportional to the congestion level of that mobile node. MAC layer congestion information has been used to determine the back-off time. Congestion was measured from MAC layer of the interface, and used this information in a way to increase the probability of selecting FNs in less congested areas of the network. That back-off time is proportional to contention window of MAC layer [17]. Since the contention window indicates how the medium is busy surrounding a node, node located in the congested area of the network will have larger contention window compared to other nodes, which are located in the less congested area of the network. During that back-off time, if they hear any broadcast of that request message, it will cancel the timer and will remain as MN. If it does not hear during the back-off time, it becomes FN and forwards that request packet to its neighbors. This process goes on until the destination packet receives that request packet. Details on FN selection algorithm can be found in chapter 3 of this dissertation. The destination node replies all requests packet that it receives through different paths. When a source node receives all the route replies, it stores those routes in its route cache. Then it starts sending data packet using the shortest hop route. A typical reduction of overhead control packet is shown in Figure 6.8. In that figure the dark nodes are MN and the other nodes are FN. The source node $S$ initiates the route discovery to find a path to the destination $D$. The dashed lines
6. CROSS-LAYER BASED MULTIPATH HDSR (CMHDSR) PROTOCOL

Figure 6.8: Broadcasting flooding in HDSR

are shown the re-broadcasts that have been eliminated by using hierarchical architecture. Since only the FN participates in the route discovery process, the source node $S$ discovers two paths $S - C - G - K - D$ and $S - U - V - W - D$. Since the number of hops in those paths are same, the source uses the first discovered path.

Once a node is in FN state, it forwards all the requests from other source. The ultimate results of that type of blind packet forwarding are (1) FN nodes may get congested when more sources use them, (2) some FNs become over utilized whether other FNs becomes underutilized, and (3) node has very limited processing power. Hence it has limited capacity to handle traffic. To overcome those limitations of 'blind forwarding', there should be some limit after that a FN should stop forwarding request packet from other sources. Based on MAC layer congestion information, a threshold value $C_{W_{threshold}}$ of contention level has been set. That kind of setting threshold value is similar to that of MDSR protocol. When a FN receives a request packet from a source and its contention level is greater than $C_{W_{threshold}}$, that FN should simply drop that request packet. But if that node has a contention level that is less than that $C_{W_{threshold}}$, it should forward that request.
6.7 The performance of CMHDSR protocol

In order to investigate how throughput is improved by CMHDSR compared to that of DSR protocol, a network topology was created with 200 mobile nodes randomly distributed in an area of $2000m \times 1000m$. Twenty UDP connections were set up among sources and destinations that are randomly selected. Constant Bit Rate (CBR) traffic is used to test the throughput. The traffic generation rate was increased from 1 packet/sec to 8 packet/sec.

The end-to-end delay performances of DSR, HDSR and CMHDSR protocols are shown in Figure 6.9. That figure demonstrates effectiveness of CMHDSR, and shows how much it improves delay compared to DSR and HDSR. One of the main reasons that CMHDSR is introduced to reduce the delay by filtering out the congested node during the route discovery phase. Obviously the delay performance of HDSR protocol is better than that of DSR protocol. Because in HDSR protocol overhead is reduced and at the same time routes along the less congested area are selected. But the delay performance of HDSR
6. CROSS-LAYER BASED MULTIPATH HDSR (CMHDSR) PROTOCOL

Figure 6.10: Delay comparison of DSR, HDSR and CMHDSR

protocol is further improved by CMHDSR protocol. For example, the delays per packet are 0.04, 0.72, 5.66, 7.80 and 8.2 seconds for DSR protocol when the packet generation rates were 1, 2, 4, 6 and 8 packets per second. Those delay values are 0.06, 0.08, 1.55, 3.32 and 4.6 seconds per packet for HDSR protocol. Those delay values of HDSR protocol have been reduced to 0.04, 0.061, 1.4, 2.83 and 3.8 seconds per packet in CMHDSR protocol. Hence for the highest packet generation rate of 8 packets/second, the delay per packet was reduced by 50% in HDSR protocol compared to DSR protocol. But that delay was further reduced by 55% in CMHDSR protocol compared to DSR protocol. The delay improvement is reflected into throughput performance, which is shown in Figure 6.10. That figure shows that the network throughput is improved significantly by HDSR protocol compared to DSR protocol. The maximum number of packets delivered to destination is 8547 in DSR protocol. But the maximum number of packet delivered to destination is 13292 for HDSR protocol. After those values, network throughput decreases when more traffic load was applied. The throughput performance of CMHDSR protocol is the maximum. The maximum number of packet delivered to the destination is 13989 for CMHDSR protocol. From the throughput
performances of HDSR and CMHDSR, it can be concluded that in the range of light traffic load (1-4 packets/second), HDSR protocol outperforms CMHDSR protocol. But after that CMHDSR protocol outperforms the HDSR protocol. Hence CMHDSR is suitable for high traffic rate. But for small traffic rate HDSR protocol is better. But in all cases, HDSR and CMHDSR protocol shows much better performance compared to original DSR protocol.

6.8 Conclusion

In this chapter, two new routing protocols were introduced namely Multipath Dynamic Source Routing (MDSR) protocol and Cross layer based Multipath Hierarchical Dynamic Source Routing (CMHDSR) protocol. The MDSR protocol shows that if highly congested nodes are prevented from route discovery mechanism, routes that are located in the less congested area are discovered. Hence the delay is improved. Moreover, when route request packets are dropped by the network nodes based on congestion level, overhead generated in the network is also reduced. Hence MDSR protocol can send more useful data packet to the destination. The MDSR protocol was combined with the HDSR protocol to implement CMHDSR protocol. The simulation results show that CMHDSR protocol shows better performance compared to DSR protocol and HDSR protocol.
Chapter 7

Concluding remarks

7.1 Summary of Contributions and comparisons

The main objective of this work has been to solve the 'flooding' problem of a reactive routing protocols. In Chapter 2, it has been shown that reactive routing protocols like Dynamic Source Routing (DSR), use a blind 'flooding' mechanism to discover paths to destination. According to that mechanism each node in the network is obliged to forward route discovery control messages that it receives from other nodes. It has also been shown that blind 'flooding' affects the performance of the network specially when network size is large. The main problems of blind 'flooding' are (1) redundant control massage generation, (2) high contention level, and (3) packet collisions. Redundant control messages occupy a significant portion of network resources like bandwidth. High contention increases delay. Packet collision increases packet loss. To reduce 'flooding' problem, many routing protocols have been proposed. Those protocols need special arrangements such as GPS system and 'Hello' messaging. Providing mobile nodes with those kind of arrangements may not be suitable. Providing mobile node with 'GPS' system incurs additional cost. 'Hello' messaging can cause additional control messages in the network. A new routing protocol called 'Hierarchical Dynamic Source Routing (HDSR)' protocol has has been introduced in Chapter 3.
HDSR protocol does not need any special arrangement like GPS system or "Hello" messaging. Hence HDSR protocol is a passive protocol. In HDSR protocol, a hierarchy among network nodes is created. Network nodes have been classified into Mobile Node (MN) and Forwarding Node (FN). MNs host the application and FNs forward the route discovery control messages. Since only FNs participate in the route discovery process, overhead control messages generated in the network are reduced significantly. An FN selection algorithm has been introduced in that chapter. MNs become FNs based on FN selection algorithm. In implementing FN selection algorithm, a cross layer design has been used. According to that cross layer design, MAC layer congestion information has been used in network layer so that FNs that are located in the less congested area of the network are selected. It has been shown via simulations that the performance of DSR protocol is improved when HDSR protocol is used.

The performances of HDSR protocol have been compared with the performances of two recently proposed protocols namely Congestion Aware routing plus Rate Adaptation (CARA) protocol [83] and Congestion-adaptive Routing Protocol (CRP) [72]. Those two protocols use congestion information to select routes that are located in the less congested area of the network. The detail operations of those two protocols have been explained in Chapter 2 of this dissertation. HDSR protocol also selects routes that are located in the less congested area of a network. But the congestion parameter of HDSR protocol is different from that of CARA protocol and CRP protocol. In HDSR protocol, congestion is measured by the contention window of MAC layer. The congestion parameter in CRP protocol is the ratio of the number of packet waiting in the queueing buffer and the size of the queueing buffer. On the other hand, CARA protocol uses MAC layer utilization. When a node tries to get access to the medium to send a packet and the medium is not busy, the MAC layer utilization is 1. Otherwise, the MAC layer utilization is 0. The MAC layer utilization is averaged for 100 samples to determine the congestion level. The delay performances of HDSR, CARA and DSR protocols are shown in Figure 7.1. It is shown in that figure that CARA protocol reduces delay per packet only by 10% compared to DSR protocol. But HDSR protocol reduces delay by 70% compared to DSR protocol. The major difference
between HDSR protocol and CARA protocol is that HDSR protocol reduces delay in two folds: (1) by reducing number of overhead packet in the network, and (2) by selecting routes located in the less congested area of the protocol. When the number of overhead packet is reduced, network resource like bandwidth is efficiently used in transmitting data packet. Hence delay is improved. The delay per packet was further improved by selecting routes located in the less congested area of a network. CARA protocol avoids congested portion of the network only. But CARA protocol does not reduce overhead in the network. Hence network resource is more efficiently used in HDSR protocol compared to CARA protocol. That is why delay is the minimum in HDSR protocol compared to that in DSR and CARA protocol. The performances of DSR, CRP and HDSR protocols are compared in Figure 7.2. That figure depicts that the delivery ratio of HDSR protocol is always better compared to DSR protocol and CRP protocol. It shows that the delivery ratio of CRP protocol is 10% higher than that of DSR protocol. But the delivery ratio of HDSR protocol is improved by 20% compared to DSR protocol. Hence it can be concluded that HDSR protocol has the least number of packet loss in the network compared to CRP and DSR protocol.

![Figure 7.1: Performance comparison of HDSR protocol with CARA protocol](image)

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Energy Saving Dynamic Source Routing (EDSR) protocol has been introduced in Chapter 4. The shortest hop routing algorithm of DSR protocol has been changed to make it energy aware. In that modified algorithm, nodes that have low energy levels are avoided while making routing decision. It has been shown via simulations that network life can be maximized if battery levels of mobile nodes are taken into consideration while making routing decision. Energy aware routing protocol has been combined with a hierarchical routing protocol to implement Hierarchical Minimum Energy Dynamic Source Routing (HMEDSR) that has been introduced in Chapter 5. It has been shown in that chapter that when a hierarchical routing protocol is made energy aware, the resultant routing protocol has some unique advantages. Since the number of overhead control message is less in a hierarchical routing protocol, network nodes are left with more energies to transmit useful data packets. It was shown via simulations that HMEDSR protocol can send more data packets to the destination compared to DSR protocol. The performance of HMEDSR protocol has been compared with other energy aware protocols such as Minimum Drain Rate (MDR) protocol [36], Energy Dependent Dynamic Source Routing (EDDSR) [23] and Localized En-
7. CONCLUDING REMARKS

Figure 7.3: Performance comparison of HMEDSR protocol other energy aware routing protocols

ergy Aware Routing (LEAR) protocol [80]. The categorical energy consumptions of those protocols are depicted in Figure 7.3. That figure shows how a node spends its energy in transmitting data packets, MAC packets and routing packets. It is shown in that figure that a node can save a considerable portion of energy in transmitting less number of overhead packet when HMEDSR protocol is used. In HMEDSR protocol, only 1% of node energy is spent in transmitting routing packet. But a considerable portion of node energy is spent in other protocols in transmitting routing packet. For example, in MDR protocol, 22% of node energy is spent in transmitting routing packet. That energy consumption by routing packet is maximum in LEAR protocol, which is 40% of node’s energy. Hence a node is left with more energy in HMEDSR protocol compared to MDR, EDDSR and LEAR protocol. Figure 7.3 shows that a node spends 80% of its energy in transmitting data packet when HMEDSR protocol is used. But a node spends only 64%, 74% and 48% of its energy when MDSR protocol, EDDSR protocol and LEAR protocol are used respectively. Hence it is depicted in Figure 7.3 that node energy is spent more efficiently in HMEDSR protocol compared to MDR, EDDSR and LEAR protocols.

In order to ensure fair load distribution among network nodes, a multipath version of
7. CONCLUDING REMARKS

HDSR protocol called Cross layer based Multipath Hierarchical Dynamic Source Routing (CMHDSR) protocol has been proposed. The limitations of HDSR protocol have been solved in CMHDSR protocol. According to FN selection algorithm in HDSR protocol, less congested MNs are selected as FNs. Once a node becomes FN, it continues participating in the network operation as long as it maintains its FN status. But an FN may become congested after supporting traffics from a number of source nodes. To overcome that problem, a limit has been set on the traffic carrying capacity of an FN. According to that limit, when an FN gets congested, it stops forwarding traffic from a new source. Thus a new set of FNs are selected.

7.2 Future work

In this work, several routing protocols have been proposed and tested by Network Simulator (NS-2). But in those simulations network nodes were static. Those routing protocols can be extended to cope with the node mobility. Node mobility causes topology changes in the

Figure 7.4: Number of hops comparison of DSR, HDSR and HMEDSR protocols
network and may affect the routing protocols proposed in this dissertation. Some of those mobility effects are as follows:

- In HDSR protocol, less congested nodes are selected for forwarding traffic of a source. But a less congested node may move to a more congested area at any time if there is mobility in the network.

- In MDSR protocol, a node might drop a request packet because its contention level was high. But that node may become less congested if some neighbors of that node move to new locations.

- In ESDSR protocol, the most energy efficient path may break due to node mobility.

To cope with those problems, efficient hand-off algorithm needs to be integrated with the routing protocols proposed in this dissertation. That kind of integration of hand-off algorithm with routing protocols can be an interesting topics to investigate in the future.
While designing routing protocol, it was assumed that underlying MAC protocol is IEEE 802.11. It is suggested in [1, 22, 27, 34] and [57] that IEEE 802.11 is not a good medium access control mechanism for ad hoc network. Those MAC protocols proposed in [1, 22, 27, 34] and [57] can be used as an underlying MAC protocols with the routing protocols proposed in this dissertation. For example, IEEE 802.11 MAC protocol has been modified to make it energy aware in [34]. That MAC protocol can be tested with MEDSR protocol proposed in this dissertation. Since MEDSR protocol is an energy aware routing protocol, it will be a good research topic to investigate the performance of MEDSR protocol when it is used with the MAC protocol proposed in [34].

The proposed protocols such as HDSR and HMEDSR have their own advantages and disadvantages. Those advantages and disadvantages are need to be further investigated in order to decide which protocol is better. The number of hop that a data packet travels in DSR, HDSR and HMEDSR protocols are shown in Figure 7.4. That figure shows that the number of hops a packet travels is maximum in HMEDSR protocol compared to HDSR and DSR protocols. When packet tarvels more number of hops, there are other issues that need
be investigated such as:

- Reliability: Packet has more chance to get lost during its traveling for many hops.

- Node activity: The number of active nodes in the network will increases because more node need to participate in the network operation. Hence node will have less chance to go into sleep mode and save energy.

- Frequent route discovery: The chance of route breakage may increase when packet travels more hops and hence there may be more route discoveries in the network.

Although packet travels more hops in HMEDSR protocol, the energy consumption is the least in HMEDSR protocol compared to DSR and HDSR protocol as shown in Figure 7.5. Hence a network will have longer life-time if HMEDSR protocol is used. The network throughput comparison is shown in Figure 7.6. That figure shows that HDSR protocol has better throughput performance compared to DSR and HMEDSR protocols. These comparisons of DSR, HDSR and HMEDSR protocol show that there are performance trade-offs. Which protocol should be chosen depends on a network's performance objectives. If reliability is the major issues, DSR protocol can be used. If energy saving is the main issue of a network, HMEDSR protocol can be used. But if network throughput is the main issue, HDSR protocol can be used. That kind of performance trade-offs need to be further investigated in future to come to a conclusion about choosing an appropriate protocol for a network.
References


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REFERENCES


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REFERENCES


[27] Heuvel-Romaszko, S.V. and Blondia, C. "Enhancements of the IEEE 802.11, a MAC protocol for ad hoc network with history of power adjustment" In the Proceedings of International Conference on Wireless Networks, Communications and Mobile Computing Vol. 1, pp. 48-54 June 2005

[28] Hu, Y. and Johnson, D. B. "Exploiting congestion information in network and higher layer protocol in Multihop wireless Ad Hoc Networks" In the Proceeding of the 24th International Conference on Distributed Computing System (ICDCS), Tokyo, Japan, pp. 301-310 March 2004


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REFERENCES


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REFERENCES


[51] Nasipuri, A. and Das, S.R. "On-Demand Multipath Routing for Mobile Ad Hoc Networks" In the Proceedings of the 8th International Conference on Computer Communications and Networks, Boston, pp.64-70 October 1999


[55] Pham, P.P. and Perrau, S. "Performance analysis of reactive shortest path and multi-path routing mechanism with load balance" In the Proceedings of IEEE INFOCOM, San Francisco, California, USA, pp. 251-259 April 2003


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REFERENCES


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[88] Zeng, K., Ren, K. and Lou, W. "Geographic On-Demand Disjoint Multipath Routing in Wireless Ad Hoc Networks" In the Proceedings of Military Communications Conference, (MILCOM), Atlantic City, New Jersey, pp. 1-7 October 2005

Appendix A

Appendix A : List of publications


A. APPENDIX A : LIST OF PUBLICATIONS


Mohammed Tarique graduated in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology (B.U.E.T), Dhaka in 1992. He has worked in Beximco Infusions Limited, Dhaka, Bangladesh as a Senior Engineering Officer from 1993-1999. He did his Master in Business Administration (MBA) from Institute of Business Administration, University of Dhaka, Bangladesh. He received his Master of Engineering (MS) degree in Electrical Engineering from Lamar University, Texas, USA. He joined the American International University of Bangladesh in January, 2007 as an Assistant Professor in Electrical Engineering. His research interests are in the area of wireless communication, ad hoc network and sensor network.