Performance Analysis of Optimal Path Finding Algorithm In Wireless Mesh Network

A thesis report submitted for partial fulfillment of the requirements for the degree of

Bachelor of Technology in Computer Science

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Certificate

This is to certify that the work in this Thesis Report entitled "**Performance Analysis Of Optimal Path Finding Algorithm In Wireless Mesh Network**" submitted by Kranti Kumar Mishra and Sunil Mishra has been carried out under my supervision in partial fulfillment of the requirements for the degree of **Bachelor of Technology in Computer Science** during session 2006-2010 in the Department of Computer Science and Engineering, National Institute of Technology, Rourkela, and this work has not been submitted elsewhere for a degree.

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Abstract

Wireless Mesh Network has emerged as a key technology for next generation wireless networking because of its advantage over other wireless technologies. Wireless Mesh Network has been widely accepted as a replacement for areas of ad-hoc network or MANET. Multi hop wireless mesh technology has become a new paradigm for communication. Wireless Mesh Network is an attractive solution for providing last-mile connectivity.

Wireless Mesh Network (WMN) consists of wireless access and wireless backbone networks. In contrast to any other network, it has low investment overhead and fast to deploy. Because of the transmission medium used in networking is radio, WMN not only provide easy and cost-effective deployment but also become realizable which is otherwise impossible for other networking technologies. Hence the IEEE 802.11 protocol has been adopted to access the fitness of the technology in various scenarios.

However, the shared nature of the transmission medium has provided certain challenges to deal with to exploit potential of the network fully. The performance of a mesh network can be assessed by evaluating various routing metrics. New metrics are also been designed to study behavior of the network in certain special scenarios. Hence over here we have analyzed most general routing metrics being used for wireless mesh networking such as: Hop Count, Expected Transmission Count (ETX) and Expected Transmission Time (ETT). In this paper we have considered only the IEEE 802.11 protocols.

WMN is a multi-hop network consisting of routers & gateways and mobile nodes. Routing in such a heterogeneous environment has put enormous challenges to participating nodes and routers to deliver packet from one corner

to other. In this thesis, we have studied various metrics for measuring routing performance. We have also studied a few dedicated mesh networks routing protocols and their accepted topologies. We have then implemented Mesh Routing Protocol (MRP) using its existing tree topology and then with modified tree and ring topology and studied their performance with respect to hopcount and Expected transmission count (ETX).

It has been observed that Tree and Modified Tree topologies have better performance when ETX was considered. But Ring topology has better performance when hopcount was taken into account. We have then considered fault tolerance of all the topologies to find that tree topology is the most fault tolerant of all the topologies. Next, one can consider other performance metrics to judge the performance of the algorithms and also use other topologies to find the difference in performance. An optimization equation can also be built taking a few performance metrics to judge the performance of the routing protocols and find the optimized.

Contents

List of Abbreviations

WSN	Wireless Sensor Network
WMN	Wireless Mesh Network
WMAN	Wireless Metropolitan Area Network
WLAN	Wireless Local Area Network
IEEE	Institute of Electrical and Electrical Engineers
PWRP	Predictive Wireless Routing Protocol
MSR	Mesh Network Scalable Routing
TBD	To be Determined
TCP	Transmission Control Protocol
ETX	Expected Transmission Count
ETT	Expected Transmission Time
WCETT	Weighed ETT
ML	Minimal Loss
ENT	Effective no of Retransmissions
DSR	Dynamic Source Routing
MRP	Mesh Routing Protocol
DSSS	Direct Sequence Spread Spectrum
AP	Access Points

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Chapter

1 Introduction

1.1 Introduction

Extending high-speed IP connectivity to the last mile is an open and on-going research with no satisfactory solution. Many existing technology lack many fundamental basis to satisfy to the problem. Full end-to-end optical networks may be a potential solution. However, initial investment costs of such wide-spread deployment and the difficulty in deployment in some environmental settings (established urban areas, wilderness etc.) have prevented its realization in real time and scalable networks. MANETs or Wireless Optical Networks are not sufficient to provide any satisfactory solution. However, Wireless Mesh Network, WMN presents an attractive alternative for this problem [4].

Wireless Mesh Network is consists of mobile hosts that generate traffic and backend routers that route traffic to desired destination. This wireless infrastructure is self-organizing, self-optimizing and fault-tolerant [5]. This has made it to connect to regions that would have been otherwise unreachable by any single access technology [4].

A Wireless Mesh Network is composed of communicating radio nodes organized in a mesh topology. It can be presented as a 3-layered network organization with *mesh clients* at the bottom most layer, *mesh routers* providing backend connectivity with distance locations and *gateways* for connecting with internet. Mesh clients are often laptops, cell phones and other wireless devices that send generated traffic to their corresponding router [4]. The routers forward traffic to and from the gateways but may not need a connection to internet. This network can be implemented with various wireless technology including 802.11, 802.16, cellular technology or a combination of more than one type.

Wireless Mesh Network can be seen as a combination of WMANs, WLANs and to certain extent WSNs. Data transmission is performed through multi-hop wireless technology involving mobile hosts, routers and network gateways. However, Wireless Mesh Networks also exhibit certain unique characteristics [5] that differentiate them from other wired and wireless technologies and put forth to revisit actual routing protocol and question their adaptability to WMN. The main differences concerns are:

- **Network topology**: Though the upper layer is made-up of mobile hosts but the underlying wireless infrastructure is static. This removes certain limitations like power constraint.
- **Traffic pattern**: Data transmission is primarily between the mobile hosts and the network gateways and traffic between two nodes are less prominent but may be considered.
- **Inter-path interference**: Inter-path interference may occur between dis-joint nodes. The communication is a point-to-multipoint as opposed to point-to-point communication in case of wired technology. Hence neighboring nodes may have impact on communication between two nodes leading to a well-known problem of hidden and exposed terminals.
- **Link capacity**: WMN link capacity may change to the very nature of wireless which is sensitive to surrounding interference. Again this is critical when multiple technologies use same frequency band.
- **Channel diversity**: WMNs can be benefited from the possibility of introducing channel diversity in the routing process which is not possible in other networks and hence reducing inter-path interference and increasing throughput [4] [5].

In WMN, where communication terminals are mobile and the transmission medium is wireless, routing is a major problem to be dealt with. The limitations on power consumption imposed on wireless radios and the fact that the communication infrastructure does not rely on the assistance of centralized stations imply that terminals must communicate with each other directly or indirectly using multi-hop routing technology. With time as the nodes move about, the topology of the network change in this distributed multi-hop wireless network. Hence we need protocols that provide efficient routing mechanism with various QoS provisions. In this thesis, we have used IEEE 802.11 protocol for various analyses [4] using several performance metrics and topologies to try to find an optimized routing protocol.

1.2 Literature Review

A Wireless Mesh Network topology can be defined abstractly as a graph G (E, V), where V represents all vertices part of the network which represents the nodes and E represents all set of edges i.e. the communication links existing between nodes [4] [32]. Since WMN is a mesh network, there exists an edge between every pair of nodes directly or indirectly. Hence we can call WMN as a fully connected network. But this network can be constructed as a k-connected network (degree of each node being k, where $1 \leq k \leq n$) for n nodes in a network considering the redundancy in the network [4].

A WMN in an architectural view can be stated as a collection of nodes with any cabling but a wireless technology. The main aim is to provide a high-speed connectivity to the coverage area. High distance transmission can be realized by means of smaller constituting network where intermediate nodes not only boost up the signal but also make intelligent decisions on packet forwarding. With this concept we categorize the WMN into three classes as follows: [3] [13]

- Infrastructure WMN: The routers form the backbone of the network.
- Client WMN: The mobile hosts or nodes form the network for routing and various maintenance works.
- Hybrid WMN: Mobile hosts perform mesh functions along with other nodes as well as accessing network [13].

Industry has adopted different view of the WMN and the difference can be made over following points: [4]

- **Network Components**: The inclusion of mobile nodes as part of the wireless mesh network architecture differentiates various views as some include mobile nodes as part of the network where as some do not. Some even consider meshing between routers and mobile nodes.
- **Degree of Mobility**: Generalization can be made between ad-hoc network and mesh network but a major difference exists which is in WMN the backbone is a non-energy constraint nodes with zero mobility but in ad-hoc network node mobility is inevitable.
- **Traffic Pattern**: The traffic pattern existing in WMN somehow resembles that of ad-hoc or WSN but the main traffic exists between internet gateways and mobile nodes.

1.2.1 WMN- A 3-Layered Network

A generalized WMN approach is a three-layered approach. The various network entities form different layers of the network. The constituting entities can be grouped in three components as: [4]

- ➢ Network Gateways: One or more gateways may be present which provide communication with other networks or internet.

- Access Points: Form the backbone of underlying network and provide various services to wireless or wired mobile hosts.
- Mobile Nodes: From the bottom-layer of the network which includes a wide variety of devices like cell phones, laptops, PDAs etc.

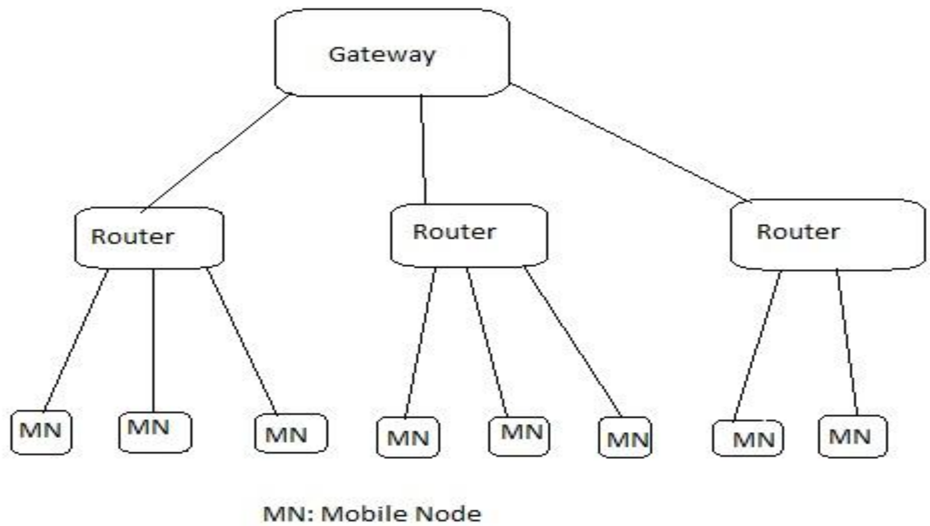

Fig1.1 Hierarchy in a Wireless Mesh Network

1.2.2 Network Topology

In a wireless mesh network all Access Points (AP) may or may not have direct connection to the network gateways. Hence they need to forward their through the network to reach the gateway. Again we may extend the access to the gateway by forming a mesh topology between the mobile nodes as happens in case of ad-hoc networking. There exists a connection between every pair of nodes in the network realm in a wireless mesh topology. There are two types of mesh topologies as follows:

- **Full Mesh Topology**: Every node is connected to every other node in the network. Full mesh topology yields greatest amount of redundancy, hence difficult to realize in a large scale using mesh routers, but small areas like small campus or offices may be ideal.

But if any router fails, then the packet can be routed through other routers. Hence the network is robust and fault-tolerant.

- **Partial Mesh Topology**: Some nodes are arranged in full mesh topology but others are only connected to one or more nodes in the network. This is realizable for small to large scale networks fulfilling the requirements. This can be of following types:
    - Point-to-Point
    - Point-to-Multipoint or Multipoint-to-Point
    - Multipoint-to-Multipoint
    - Metropolitan
- **Mixed Node Topology**: A mixed node topology is the complex form of wireless network which is composed of two radios and two high gain antennas in direct communication with each other and a third party wireless bridge/repeater. Though the links are quick to deploy but not scalable to create a large network. Clients may use these bridge/router nodes in an indoor environment and the main benefit so achieved is low installment cost.

Topology of the mobile nodes has a great impact on the performance of any routing protocol of WMN. Logical Arrangement of nodes under an AP and arrangement of routers in the network plays big role in packet transmission. The routing algorithms are been broadly classified basing upon following criterion: [4]

- **Routing Philosophy**: Routing approaches can be viewed as proactive, reactive and hybrid type. In proactive ones, paths are established regardless of if there exist any data to transmit. In reactive, path is established on-demand. Hybrid protocols implement both type of path establishment.
- **Network Organization**: Network may follow flat organization where all nodes have same role to play but in hierarchical

organization some nodes may have specialized functions. Super nodes may exist for various network management works.

- **Location Awareness**: Routers may or may not have any information about location of various nodes in the network.
- **Mobility Management**: WMN has to manage the mobility of nodes throughout the network. As nodes move about, they change their logical position, the corresponding they attached to. But there exists several issues that need to be taken care of separately.

1.3 Organization of the Thesis

The whole thesis is organized into 6 chapters. Chapter-1 presents an introduction to the theoretical concepts of the WMN. Chapter-2 provides the details of routing in WMN. It also presents WMN with respect to existing routing protocols and various performance parameters used to estimate its performance. Chapter-3 deals with the existing protocols, the topologies and the algorithms which we have implemented in our simulations. Chapter-4 presents the results obtained by using the pre-existing topology for purpose in the experimental environment and comparing it with 2 other topologies with respect to certain performance metrics.. Chapter -5 deals with the fault tolerance capabilities of all the three topologies and their comparison. At the end, the thesis states any modifications or enhancements that can be done in future and next follows the reference section.

1.4 Conclusion

This chapter presents a general overview of Wireless Mesh Network along with its unique features and similarities with existing technologies. The background for this thesis work is given. Though there are two types of WMN, we have considered only static network. This network can solve both the problem of distributed networking and fault-tolerance.

Chapter

2 The Routing Problem

2.1 Introduction

The main aim of the wireless mesh networking is to transmit data over a long range without any failure. This problem can be handled by dividing the problem into sub-problems i.e. by handling the problem by constituting network of the larger network. And the routing protocols state rules for handling the problem. In order to access the performance of any routing algorithm, we have designed various parameters or performance metrics.

To ensure good performance, every routing metrics need to satisfy following four requirements which are as follows:

- *Routing metrics* should not frequently change routes to ensure stability of the network.
- *Routing metrics* must adhere to WMN characteristics to ensure that minimum weight paths have good performance.
- *Routing metrics* must ensure that efficiency in finding minimum weight path with polynomial complexity bound.
- *Routing metrics* must ensure that forwarding loops are not formed by routing protocols.

2.2 Performance Metrics

Depending upon the network characteristics, various performance metrics have been proposed to ensure efficiency and optimization in network management and throughput. And protocols can focus on certain aspect of the network to optimize one or more metrics. Now we introduce few most commonly used metrics as follows: [2] [4]

- **Hop Count**: It is the most commonly used metrics in wireless multi hop networking. Hop count refers to the no. of intermediate nodes in the path as the packet travels from source to the destination [33]. This metrics counts good performance in ad-hoc networking as the performance mainly depends upon route length. However, this metric fails due to the heterogeneous nature of mesh network. This metrics even do not consider the congestion resulting from the shared use of the transmission medium [33].
- **Blocking Metric**: Blocking values of a node is defined as the number of neighbors a node is interfering with. Blocking metric for a path is also defined as sum of blocking values of all the nodes in the path. Then the path with minimum value may be taken up for data transmission. Though this is very simple to manage but additional overhead occurs to maintain such large information for each and every node. This also do not consider unique characteristics of mesh network involving traffic flow or link capacity and has no or little consideration towards interference issue.
- **Expected Transmission Count (ETX)**: This metric accounts for data loss due to medium access contention and environmental hazards and considers the no. of transmissions needed to transmissions needed to successfully transmit a packet over a link. Hence this metric is more specific for wireless technology. Expected Transmission Count is defined as the number of transmissions required to successfully deliver a packet at the destination over the wireless link. ETX can be measured as the sum of ETX value of every link in the along the path. Let's assume p_f and p_b be the packet loss probability in forward and backward direction respectively. Hence the probability of an unsuccessful transmission is:

  $$\mathbf{p=1-(1-p_f)\,(1-p_b)}$$

  Therefore expected no. of transmissions required to successfully deliver a packet can be defined as: [37] [33]

$$ETX = \sum_{K=1}^{\infty} k\, p^k (1 - p)^{k-1} = 1/(1 - p)$$

The delivery is measured by using 134-byte probe packet. One probe packet is sent every 7 seconds. Packet loss ratio is computed by counting no. of packets received over a predefined period (10seconds). Hence it favors paths with higher through-put. However this metric does not consider the different bandwidth and channel availability. It is not even good to predict the how busy the channel is and give no information regarding effective sharing of links.

- **Expected Transmission Time (ETT)**: This on can be regarded as an enhancement to existing ETX metric. It also considers the bandwidth and channel allocation to favor channel diverse paths. If S is the packet size and B is the bandwidth, then ETT of the link is considered as:

  ETT=ETX*S/B

  Similar to ETX, ETT can be computed as the sum of all the links ETT along the path [38].
- **Minimum Loss (ML)**: This metric is based on probing to the computer the delivery ratio. In contrary to ETX, ML searches for a path with the lowest end-to-end loss probability and hence it is not additive in nature. Rather it multiplies the delivery ration of every link in the path in both forward and reverse directions and finds the best path and hence ensures a path with overall reasonable performance and reduces the number of route changes.
- **Effective Number of Retransmissions (ENT)**: ENT is an alternative approach to measure the number of successive retransmissions per link considering the variance. ENT also broadcasts probes and limits route computation to links that show an acceptable number of expected retransmissions according to upper-layer requirements. ENT excludes any

link that shows transmission higher than the maximum tolerated by any upper-layer protocol by assigning it an infinite metric[39].

- **Weighted ETT (WCETT)**: This metric provides a good approach to measure multi-channel WMNs with inter-flow and intra-flow interference. Intra-flow interference occurs when different nodes transmitting packets from the same flow interfere with each other. Thus maximizing the number of channels is not trivial but the nodes must maintain connectivity throughout. Inter-flow interference otherwise is the interference suffered among concurrent flows. The weighted cumulative ETT (WCETT) changes ETT to include intra-flow interference. So we can view this as a sum of end-to-end delay and channel diversity [33]. But this parameter can be tuned by either combining both of them or prioritizing one of them. It considers end-to-end path so as to choose a path with low intra-flow interference. But it does not guarantee shortest path or inter-flow interference [33].
- **Energy Consumption**: If nodes are energy constraint, then energy level of nodes can be considered as a parameter which must be maintained else failure may occur. However this problem is specified for the mobile nodes not for the routers as they are static in nature but it is important for WSNs and MANETs.
- **Bandwidth**: A network may accompany many networks with different data rates. This issue needs attention else the performance would degrade due to external environmental noise and signal strength. Again all possible channels may not be available due to technical limitations. This difference in capacity has an effect not only on the link considered but also on the capacity of geographically close links. Again, the use of links with lower capacity increases both transmission delay and reduces achievable rate of neighboring transmissions by increasing interference level. As the present hardware allow rate adaption depending on the quality of the

transmission medium, obtaining and maintaining this information can significantly improve the performance.

Additional complexity arises as routing and channel allocation are subjected to following two constraints as follows:

- Considering the heterogeneous nature of the network, the channels and path chosen must ensure data delivery for every pair of source and destination.
- Links in the selected path may use different channel and frequency, hence routing protocols must deal with the issue.

The routing problem of static wireless mesh network can be decomposed into following four sub problems whose solutions may be later combined to find the optimal solution for the network. These sub problems may or may not have a solution and even these solutions may not be optimal ones, but they add credit upon the fact that the main problem gets simplified. These sub problems are as follows:

- **Topology Sub-problem**: Transforming the physical topology of the nodes to logical topology such that resulting configuration presents a simpler arrangement of nodes to deal with.
- **Routing Sub-problem**: Determine the physical link between the source and destination pair over the logical topology.
- **Channel Allocation Sub-problem**: Routing protocols must allocate channels to eradicate the noise and interference issues.
- **Traffic Maintenance Sub-problem**: Determine the path with low traffic to route data from source and destination.

In this thesis we have approached first two sub problems, where we have analyzed the performance of various routing protocols. The combined Routing and channel allocation is a hard problem, but it is simplified by decoupling it into two sub-problems: the routing problem and the topology sub-problem. In this section, we focus on various approaches to routing connection requests.

2.2.1 The Routing Sub-problem

The routing protocols developed so far follow two approaches which are:

Fixed Routing

This is the simplest approach wherein the route from each source to every destination is fixed [34]. This path is calculated offline using standard shortest path algorithm like *All-pairs or Dijkstra's algorithm* or *Bellman-Ford algorithm*. Hence the node does not need to store the global network state.

On receiving a connection request, the network tries to establish a connection along this predetermined path. If no common wavelength is available on every link on the route, then the connection is blocked. This might result in high blocking probabilities in the dynamic case or may result in a large number of wavelengths being used in the static case. For minimizing blocking, the fixed routes must be so chosen as to balance the load evenly across the network links. Also a single link failure will block all the routes passing through it.

Adaptive Routing Schemes

These schemes try to overcome the disadvantages of the fixed routing schemes by taking into account network state information. These schemes require extensive support from the control and management protocols to continuously update the routing table at the nodes [34].

2.3 Routing Protocols

Only few protocols have been developed for WMN so far. We have considered two protocols two protocols here. MIT (SrcRR) and Mesh Networks (Mesh Network Scalable Routing) are the new protocols developed for WMN. MSR (Mesh Network Scalable Routing) are the new protocols developed specifically for WMN. This can support highly mobile users and can adapt to changing network conditions. Since this is a proprietary protocol, we have no way to access or modify the requirements. SrcRR, developed by MIT is a simple variation of DSR where it uses expected transmission time as a metric instead of hop-count i.e. the shortest paths are determined based upon least packet loss path. Much work has been done towards enhancing existing protocols and developing new metrics to suit WMN. The next table shows few protocols available for WMN.

Routing Protocols	Proactive	On-demand	Flat	Location Awareness	Metrics	Integrated Mobility
MSR	X	X	X	No	Proprietary	Yes
SrcRR		X	X	No	ETT	-
PWRP	X	X	X	No	Proprietary	-
MRP	X		X	No	TBD	-

Table 2.1: Routing Protocols in WMN [4]

2.3.1 Mesh Routing Protocol

This protocol takes advantage of the very characteristic of WMN that the major traffic flow exists from and to gateway and to internet. The major concern i.e. the forward and back-path routing needed to be handled whereas the traffic between clients is negligible. The route to and from the gateway can be seen as a tree with gateway as the root.

For a small deployment like LANs in offices or departments, there are mobile nodes that move about gateways. Every client chooses a single gateway to connect as soon as they move or the gateway fails. Among all gateways, there exists a super-gateway which is connected to internet. Hence all traffic from and to network to internet is routed through the super-gateway and the network can be seen as a tree rooted at this gateway. There exist three versions of MRP which are as follows:

- **MRP-On-Demand**: When a nodes wishes to join a network or to transmit some data, it would ask its neighbors or nearest gateway for a route. Since all joined nodes have information about every route, hence there is no difficulty for searching for a new path and as soon as a node chooses a route, it can commence its transmission. As the node registers itself to its chosen router or gateway, it becomes a part of the network.
- **MRP-Beacon**: It is a modified version of MRP-On-Demand. In this protocol, nodes that no longer participate in network, their corresponding path gets deleted. Again, any node wishes to join the network, does not send request packets but listens for beacon packets and collects beacon packets. Hence it can get information about routes and can later register to the router and start transmission.
- **Hybrid MRP**: Hybrid MRP is a combination of both MRP-On-Demand and MRP-Beacon. Any node wishing to join network, sends request packets and listens to beacon packets. This way it collects route information and can later register with corresponding route. It has better performance than either of MRP-On-Demand or MRP-Beacon and it has implemented route error handling mechanism.[6]

2.3.2 SrcRR Protocol

SrcRR is a reactive routing protocol with source routed data traffic, similar to DSR with link cache. Whenever any change is made to the link cache, the nodes locally run Dijkstra's weighted shortest-path algorithm on their database to generate new and optimal path to all other nodes in the network. To ensure that only fresh information is used for routing those paths are dropped which have not been updated for a certain period.

Route discovery is done by flooding. Nodes take care to forward only those route request packet which are more probable to generate better path. When any node forwards a data packet, it updates its entry to contain the latest information of the path in the link cache. So whenever the performance of that path degrades an alternative route may be chosen for routing. Every query and data packets carries ETX information of the nodes they have traversed so far and this information are used to update link cache of receiving node [7].

2.4 Conclusion

In this chapter, we have discussed the routing problem and how this problem can be addressed by breaking down into sub-problem such that they can be addressed individually. Again we have discussed two protocols i.e. MRP and SrcRR which are particularly made for mesh networks. The next chapter introduces the various strategies undertaken to optimize the routing problem. Though many metrics can be used for measuring performance of the routing protocols, we have tried to optimize the protocols by changing the topology of the mobile nodes present under a router.

Chapter

3 Implementation of WMN Path Finding Using Different Topologies

3.1 Introduction

The path finding problem is defined as finding a path from a source node to a destination node in a Wireless Mesh Network so as to optimize the transmission. Here, we use the Mesh Routing Protocol (MRP) using Dijkstra's Algorithm to find the path between routers. We implement the MRP with several topologies and study two performance metrics to optimize path finding in WMN.

3.2 Fundamentals of Mesh Routing Protocol (MRP)

In WMNs, most traffic is generated from node to the gateway (to the Internet) and vice versa. Thus, in MRP any node needs to know only the path to one router which in turn can find the path to the destination router. Each node here is considered to be under the influence of only one router and even if two routers have under their range the same node, only the router with the stronger signal to the node is allowed to communicate with the node directly. Any small amount of traffic between two nodes under the same router is also channeled through the common parent router. So we can assume the routes to and from the router to be in the form of a tree rooted at the router.

The nodes are considered mobile in WMN and if a node moves or a router fails, the node may choose a different router to transmit data in the network. The routers are considered to be static, infrastructure and wired to each other and linked to one gateway that is then connected to the outside world (Internet). All nodes are free to move about as long as they are under the coverage of one router. MRP messages are transmitted through UDP packets for the reason that TCP overhead and delay are too high for a Wireless Network. Three versions are explained in brief below. Each of the protocols uses routing table changing calls to account for mobile nodes [5].

3.2.1 MRP On-Demand

This version of the protocol is as the name suggests, On-demand, i.e. a reactive protocol. When a node joins the network or moves from the coverage of one router to another, it asks only for its closest router or neighboring nodes for a route. This is done via a local broadcast of Route Discovery (RDIS) message. The packets are not flooded in the network, and are only received by immediate neighbors (one hop transmission) of the entering node. The neighbors by this point know the path to the router and through it the gateway and the efficiency of the various paths in the network. Each of the nodes receiving the RDIS message replies with a route advertisement (RADV) message with a random delay from one another (to avoid collision). Once the node receives all the RADVs, it selects one or more routes as a function of its requirements and efficiency. The node then registers with the router it comes under. The registration has the main function of providing the reverse path. The registration process takes place via two steps. In the first step a registration request (RREG) is unicasted by the node to the router. The intermediate nodes here register the path from the node to the router to help during the return path. The router upon receiving the RREG sends a registration acknowledgment (RACK) directly to the joining node and also forwards the RREG to the gateway (enabling the gateway to decide which path to take in case of transmission from the Internet to the node).Upon completion of the entire process mentioned above, the node is said to be in *completely connected state.* In case of any loss of packets during the entire communication, the entire process has to repeat again starting from the route acquisition process [5].

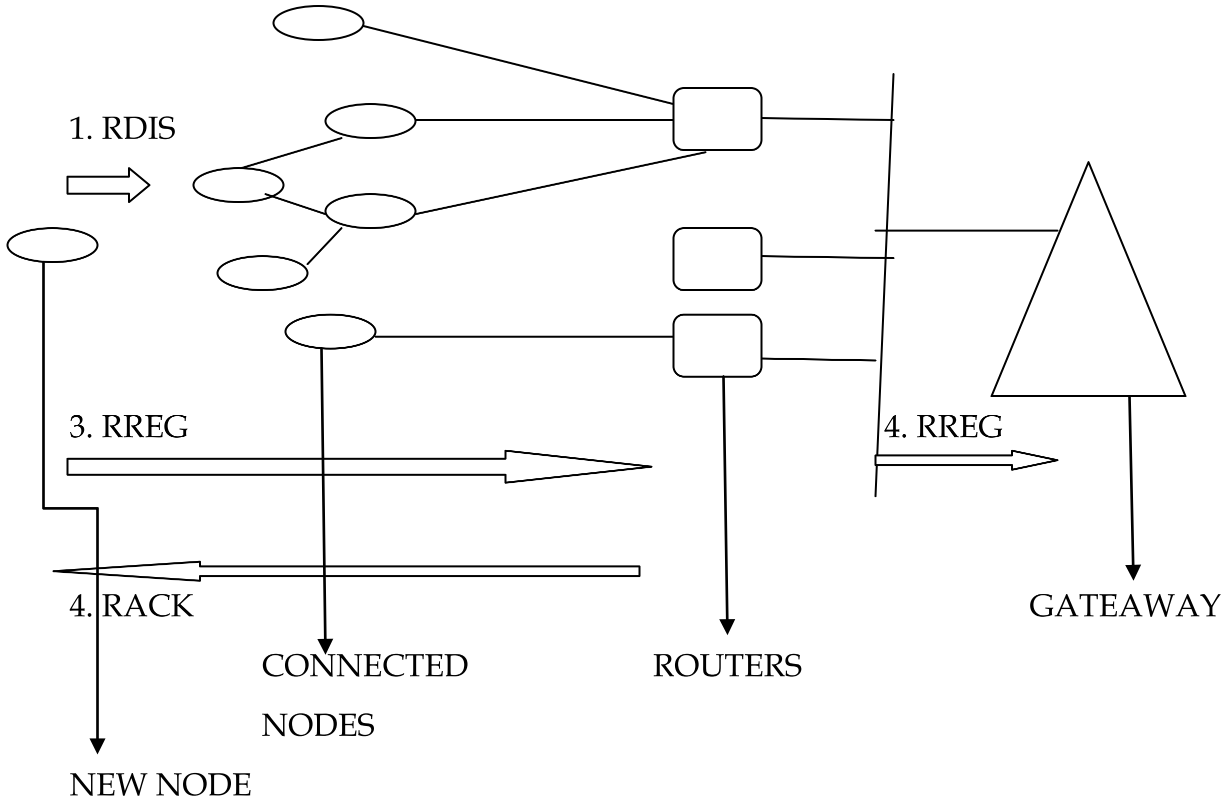

Fig 3.1 MRP route establishment message sequence

3.2.2 MRP Beacon Mode

The problem with MRP-On Demand is that when a node doesn't send any packets, it cannot detect the validity of the node. Due to this any data from the Internet or from other nodes cannot reach the node in question. This version of MRP uses beacons to keep track of routes; each completely connected node periodically sends beacons advertising the available routes. This beacon is different from the beacon sent by the 802.11 protocol since that acts on the MAC layer and this beacon acts on the routing information on the network layer. IN this version, when a node wishes to connect to the network, it doesn't have to send RDIS. It simply listens to the neighboring nodes from slightly more time than the beacon period and gathers information through the collected beacons. To detect disconnection, in addition to relying on packet forwarding failure it utilizes the beacon messages originally sent during route setup process. Each node notes the number of beacons sent from their parent node/router and if a predefined number of beacons are missing, then the node is said to be disconnected from the network. There is a trade off between the time interval with which the beacons are sent and performance of the protocol. But this version detects disconnections faster and thus is expected to have better performance during low traffic flow and still suffers from high overhead. [5]

3.2.3 MRP Hybrid

In this version, the features of both the versions mentioned above are used to get the better of the two. Here, the joining node broadcasts route discoveries (RDIS) and waits for route advertisements (RADVs) for a time interval equal to the minimum between the random delay of the MRP-on demand and the beacon period of the MRP-beacon mode. The received RADVs include those generated in response to the RDISs, as well as the beacons. The joining node then selects the route and registers with the router. This version is expected to perform better and either of the above two and detects routes faster:

Since none of the three versions uses flooding during any phase, this protocol is highly scalable to bigger networks [6].

3.3 Dijkstra’s Algorithm

Dijkstra's algorithm solves the single-source shortest-path problem when all edges have non-negative weights. It is a greedy algorithm and similar to Prim's Algorithm. For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex. It can also be used for finding costs of shortest paths from a single vertex to a single destination vertex by stopping the algorithm once the shortest path to the destination vertex has been determined. Algorithm starts at the source vertex, s, it grows a tree, T, that ultimately spans all vertices reachable from S. Vertices are added to T in order of distance i.e., first S, then the vertex closest to S, then the next closest, and so on.

The following algorithm describes the process using certain parameters which are also explained in the algorithm.

```
Algorithm Dijkstra(v,cost,dist,n)
// dist[j], 1 ≤ j ≤ n, is set to the length of the shortest path from vertex v to the
//vertex j in a diagraph G with n vertices. dist[v] is set to zero. G is represented // by cost adjacency matrix cost[1:n, 1;n].
 {
        for i :=1 to n do
        { // Initialize S.
                S[i]:=false ; dist[v]:=0.0 ; // Put v in S.
        }
        for num :=2 to n do
         {
                //Determine n-1 paths from v.
                Choose u from among the vertices not in S such that dist[u] is minimum.
                S[u] := true; // Put u in S.
                for ( each w adjacent to u with S[w] =false) do
                // Update distances
                If(dist[w] > dist[u] + cost[u,w] ) then
                        dist[w] := dist[u] + cost[u,w] ;
        }
}
```

Fig 3.2 Dijkstra's Algorithm

3.3.1 Implementation in WMN Routing

The path finding algorithm in the setup has been divided into three parts. The first part is the path from the source node to the source router, the second from the source router to the destination router and the third from the destination router to the destination node. The first and the third part of the algorithm deal with the topology of the mobile nodes which has been explained afterwards. The second phase deals with the path from the source node to the destination node which we have found using Dijkstra's Algorithm. The router's connection with other routers and the gateway is the static part of the Mesh Network which is considered to be static. They are mostly connected via wires to minimize energy constraints of the mesh routers and the gateway. Thus the network is permanent and can be represented by a graph which is then used in the Dijkstra's Algorithm.

3.4 Topology of Mobile Nodes

MRP assumes the mobile nodes to be arranged in the form of a tree (hierarchical manner). Topology of the mobile nodes is to be considered as a parameter for the WMN routing protocols as WMN allows for *multi hop communication* i.e. even if a node is not directly under the range of a router; if it is near enough to another node which is in the network currently, then data can be transmitted indirectly to the router through the nodes present in the network. We have assumed three different topologies for the mobile nodes entering under each router and compared performances of the three topologies using performance metrics such as ETX (Effective Transmission Count), hop count and fault tolerance. The three topologies considered are:-

3.4.1 Basic Tree Structure

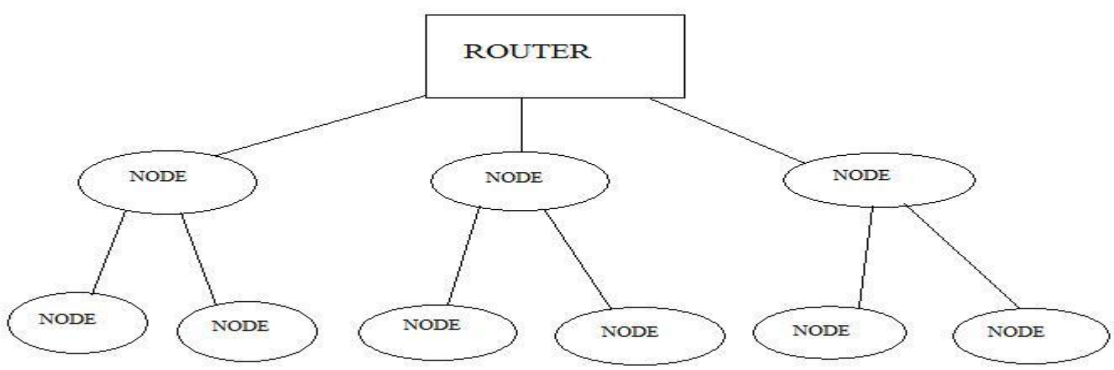

Fig 3.3 Tree Topology

Each of the ellipses in the above figure represents a mobile node. The root represents the router under which all the nodes communicate. This is the basic topology which MRP implements. This topology can be setup in the following way in the network:

When the first three nodes (direct fan out of the router(assumed)) arrive under the router, they are attached directly under the router and form the first level nodes under the router. The next nodes arriving are attached to these nodes and connection is setup. The path finding in tree topology of the nodes can be done by implementing the tree structure in an array data structure and finding the root through repeatedly finding the parent node. In the destination side, the path to the destination node can be found by BREADTH FIRST SEARCH (BFS) of the tree structure at the destination side router.

3.4.2 Modified Tree Structure

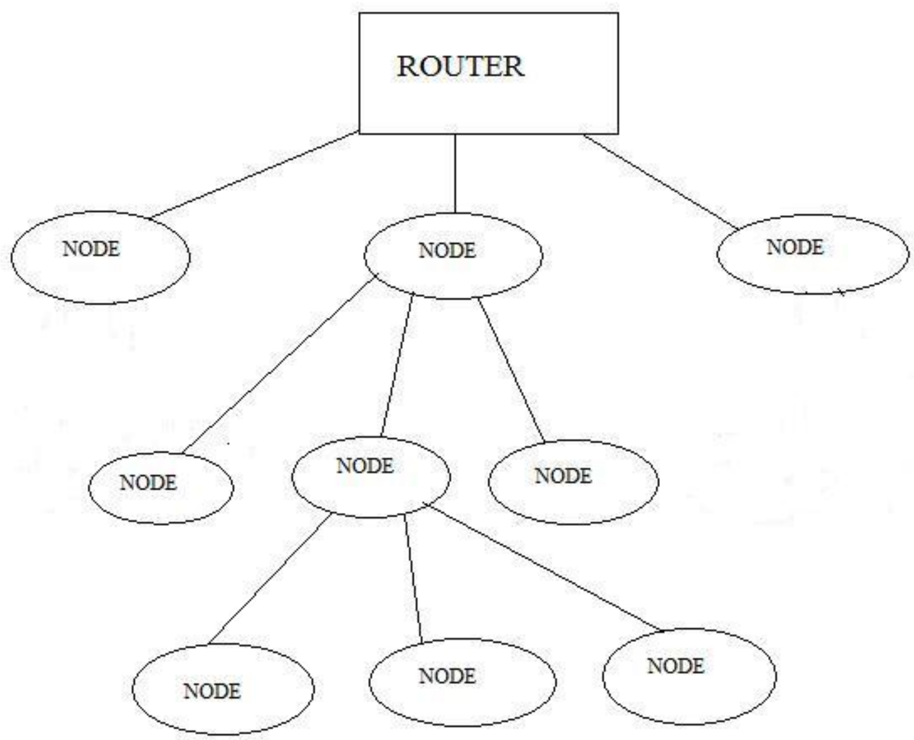

Fig 3.4 Modified Tree Topology

As in the above topology, each of the ellipses represents a node. This is a modification of the general tree structure with the addition of the criterion that only one of the child nodes can propagate nodes further down the network. Though this seems to be an inefficient design since it obviously increases the average hop count of the system, the range of the system increases with this topology. The topology can be setup in the same way as the tree structure with the added condition that from each level of nodes, only one node can have a set of child nodes. The path finding strategy in the modified tree structure is different from the tree structure. In this topology, at the source side, the implementation is the same as in the case of the tree topology (repeated parent node finding). But at the destination side router, the algorithm to find the destination node becomes simpler as the BFS is modified, to check the child nodes of only one of the nodes at each stage.

3.4.2 Ring Structure

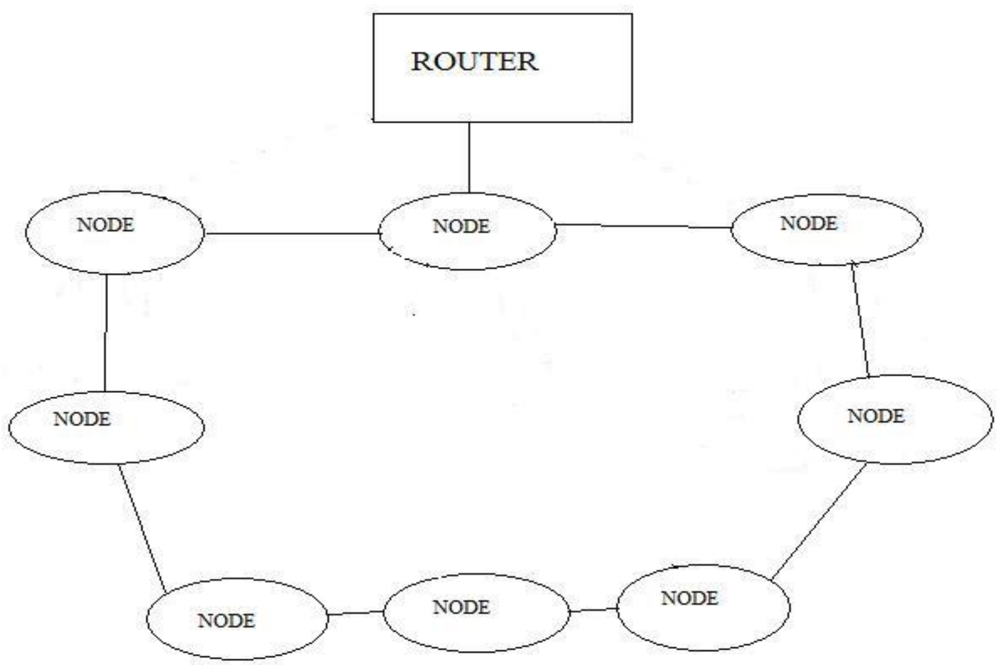

Fig 3.5 Ring Topology

The Ring structure is one of the most common structures in wired LANs. This is an entirely different topology from what has been previously implemented in MRP. This topology can be generated in the network in the following way:

The first node which comes into the network is associated directly to the router. Every next router which enters into the network is then connected to the node which came into the influence of the router just before the current node. This iterative process continues till the last node enters the network which after being connected to the network via the previous node, connects to the first node to complete the Ring structure. The Ring Topology's disadvantage is the fact that when one of the node fails, the entire network of nodes under the router are in jeopardy and the reconfiguration has to take place before any transmission in the network is possible. The path finding at both and destination is done very differently in this case than the previous two algorithms. At the source node, the node checks the routing paths available to it for reaching the router. The better path is then chosen based upon hop count and transmission takes place. At the destination, the router checks its routing table to determine the path from the two available. Then data transmission to the destination takes place in the more efficient path.

3.5 Conclusion

In this section, three topologies have been suggested to be implemented by the mobile nodes under a router in a Wireless Mesh Network. The network is supposed to have implemented the Mesh Routing Protocol (MRP) and finds the path from one router to another through Dijkstra's Algorithm. The path finding within a router is different in each topology. In the next chapter, we test each of the setups for reliability, fault tolerance and efficiency through a defined simulation scenario.

Chapter 4 Simulation Setup and Results

4.1 Introduction

The path finding problem has been implemented using Mesh Routing Protocol (MRP) and Dijkstra's Algorithm described in the previous chapter. The simulations have shown the effect of the different topologies on the various performance metrics of WMN. The Routing problem has multi-objective optimization in case of Hop Count, Expected Transmission Count (ETX) and time taken for network topology to re arrange itself in case of node failure. The first topology considered is the Tree topology which is the general topology used in MRP. Next a modified Tree structure is used in which only one node in each level has a child nodes attached to it. Finally, a Ring Topology has been used. The performance metrics studied are:

1. **Expected Transmission Count (ETX):** It accounts for data loss due to medium access contention and environmental hazards, and considers the number of retransmissions needed to successfully transmit a packet over a link.
2. **Hop Count:** Hop count is the most commonly used metric in wireless multi-hop networks. The path selected is the one minimizing the number of links between a given source and destination node.

The performance of all the topologies for different topology in the mobile node networks with respect to the above parameters is compared in this chapter.

4.2 Simulation Setup

The simulation considers a setup with a three stored building serviced by nine routers, three on each floor. The simulation also considers the presence of a gateway on the second floor connected to one router on each router so as to provide path to the Internet from all the routers. This arrangement considers minimum interference between routers located on the same floor as well as routers in the neighboring floors. It also eliminates the bandwidth contention that occurs when two routers with overlapping coverage are configured with the same channel. When this happens, 802.11 wireless Ethernet carrier sense multiple access/collision avoidance (CSMA/CA) mechanism ensures that users in both access areas can access the network. The setup assumes 90 mobile nodes to be present in the building (30 nodes on each floor). It is assumed that all the mobile nodes are free to roam about as long as they stay in their respective floors. It is also assumed that that all the nodes in a floor do not at any point converge to come under a single router and that all the routers have some nodes connected to them at all time.

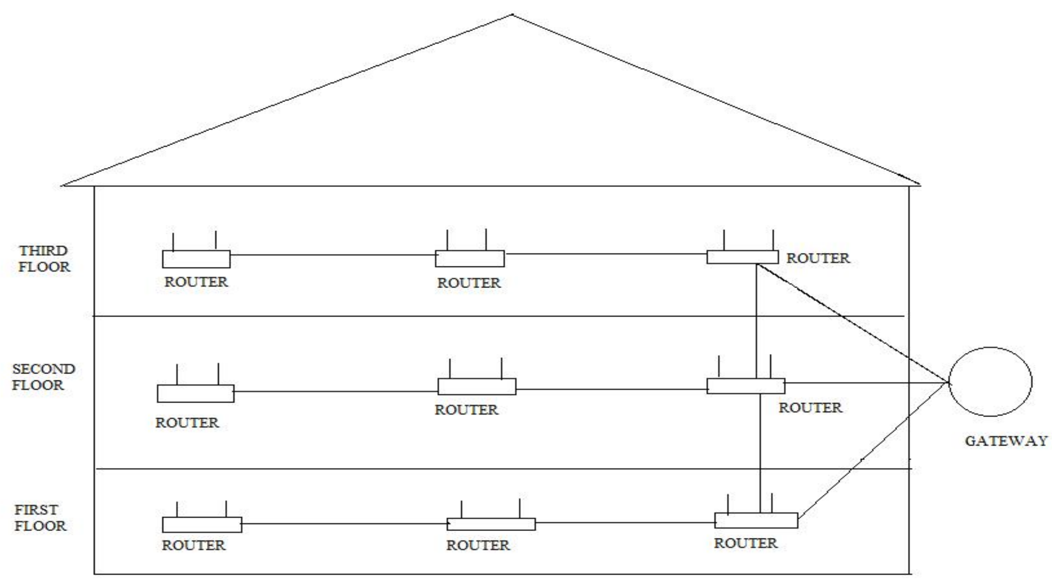

FIGURE 4.1: mesh infrastructure of the routers and gateway

The setup currently considers the system to be fault resistant though later we explain the rearrangement of nodes in case of a router or node failure.

For communication purposes in a Wireless Mesh Network, multi hop and multi frequency communication are important. For this to happen, each node or router has to process more than one request at a time. We have assumed each router to be capable of handling 4 requests at a time (due to presence of multiple frequencies) and the nodes to be able to attend to only one request at a time.

4.3 Standards Assumed

The simulation considers various standards for the packet communication in the network, frequencies allocated to each router and the amount of multi frequency communication that takes place in the router. The standards are explained below:

4.3.1 IEEE 802.11a Wireless Networks Protocol

IEEE 802.11a is a set of standards carrying out wireless local area network operates in the 5 GHz band with a maximum net data rate of 54 Mbit/s, plus error correction code, which yields realistic net achievable throughput in the mid-20 Mbit/s. Since the 2.4 GHz band is heavily used to the point of being crowded, using the relatively unused 5 GHz band gives 802.11a a significant advantage. However, this high carrier frequency also brings a disadvantage: the effective overall range of 802.11a is less than that of 802.11b/g. In theory, 802.11a signals are absorbed more readily by walls and other solid objects in their path due to their smaller wavelength and, as a result, cannot penetrate as far as those of 802.11b. In practice, 802.11b typically has a higher range at low speeds (802.11b will reduce speed to 5 Mbit/s or even 1 Mbit/s at low signal strengths). However, at higher speeds, 802.11a often has the same or greater range due to less interference. The 802.11 standards cover definitions for both MAC (Medium Access Control) and Physical Layer. The standard defines a single MAC, which interacts with Direct Sequence Spread Spectrum (DSSS). For proper functioning of the WMN, neighboring cells are set on different frequencies, so that the wireless LAN cards don’t interfere with each other when they transmit signals. In order for cells to do work without interference, DSSS defines 13 different frequencies for channels. They frequencies are typically "non- overlapping" i.e. they operate on different sections of the radio spectrum. So, we have assumed 13 as the maximum number of cells or mobile nodes that can operate under a single router [34].

4.3.2 Input Traffic Variations

We have considered Poisson Distribution of Traffic as input varying values of lambda from 5(light traffic) to 50(heavy traffic).

4.4 Simulations

The simulations for the three topologies are given below:

4.4.1 Tree Topology

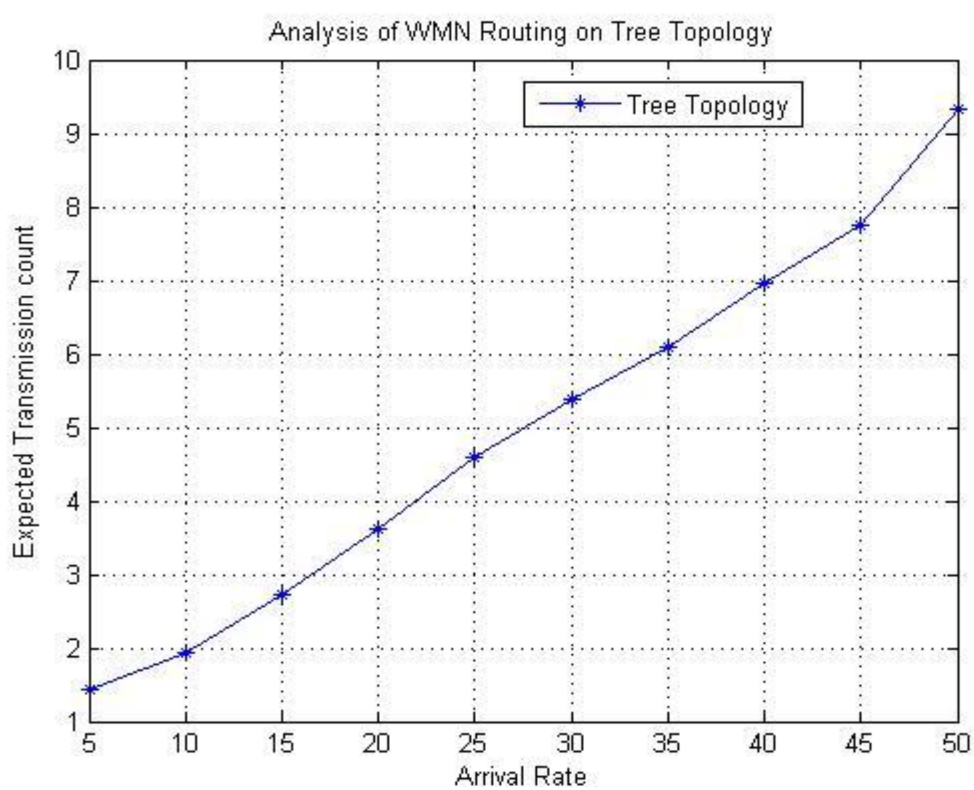

Figure 4.2: ETX for Tree Topology for varying values of Lambda

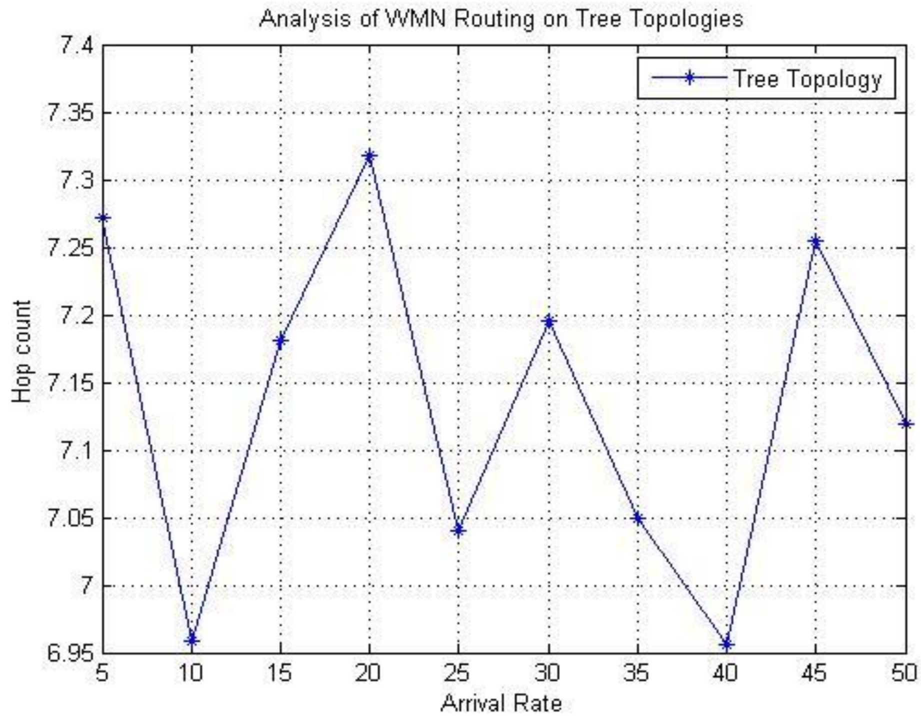

Figure 4.3: Hopcount for Tree Topology for varying values of lambda

4.4.2 Modified Tree Topology

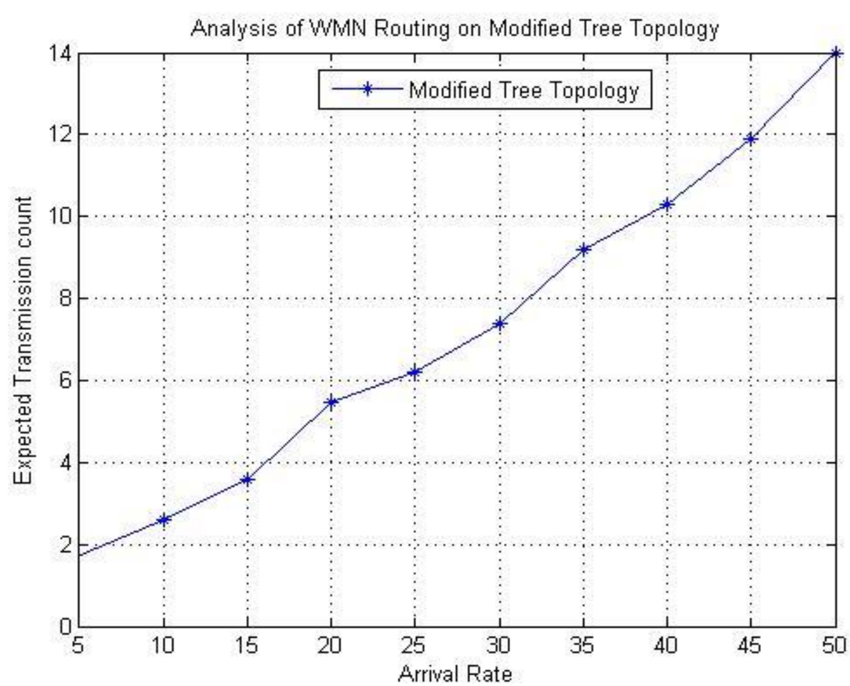

Figure 4.4: ETX for Modified Tree Topology for varying values of Lambda

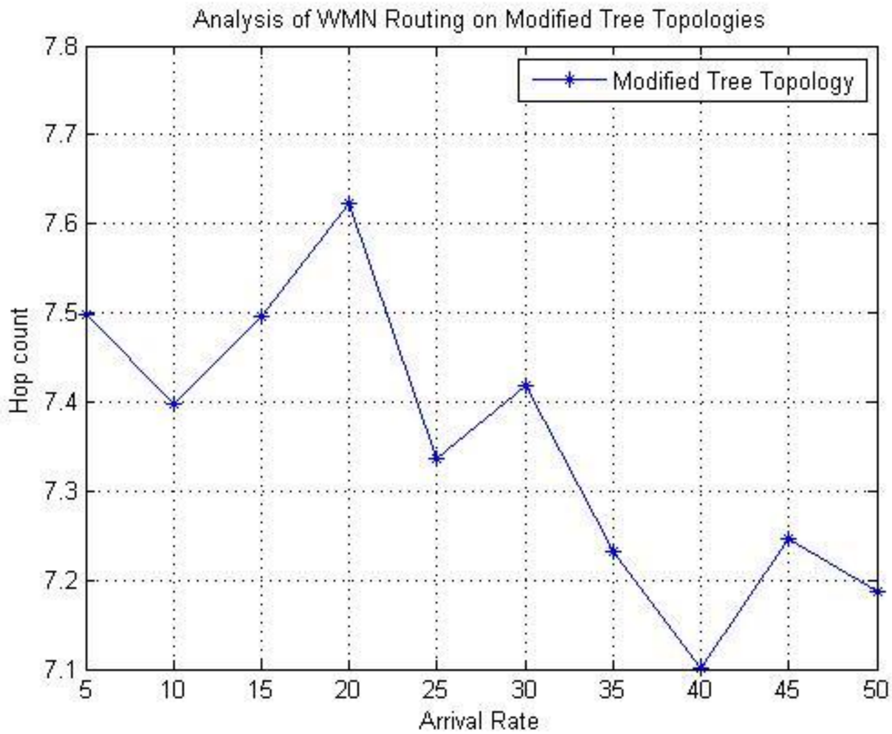

Figure 4.5: Hopcount for Modified Tree Topology for varying values of Lambda

4.4.3 Ring Topology

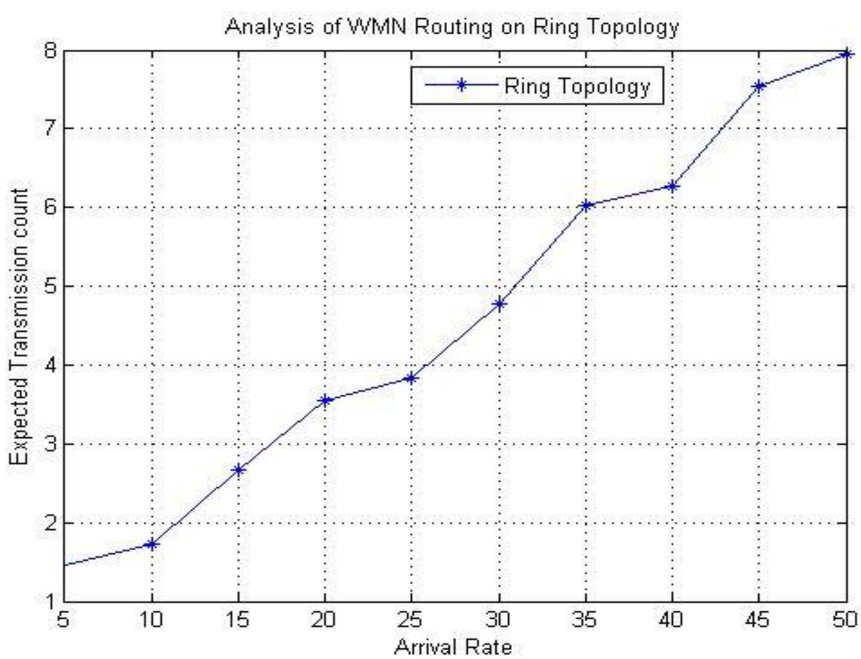

Figure 4.6: ETX for Ring Topology for varying values of Lambda

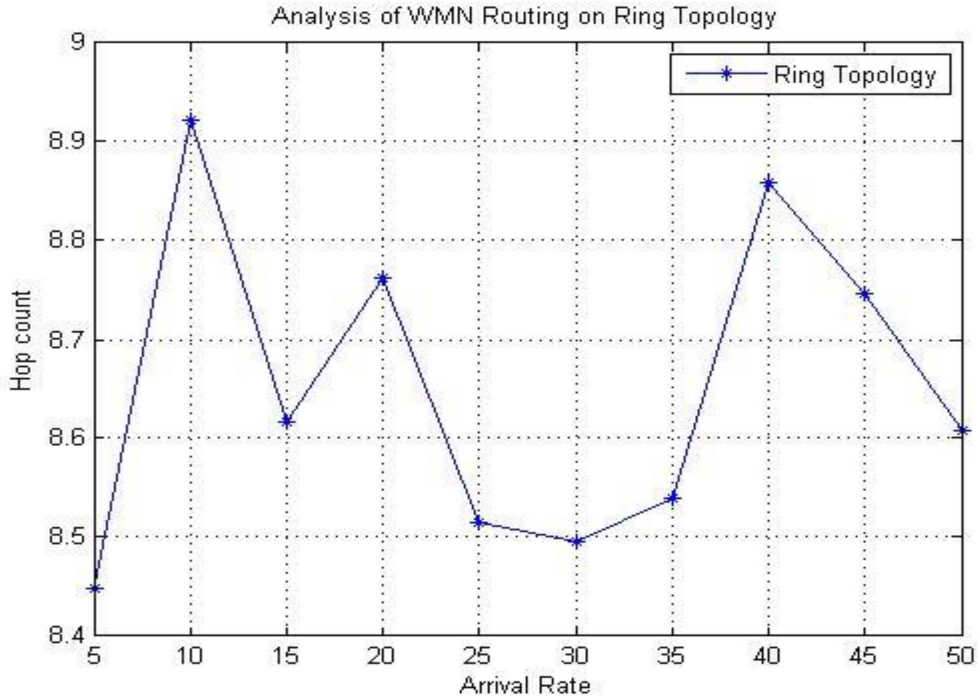

Figure 4.7: Hopcount for Ring Topology for varying values of Lambda

Lambda	Ring		Tree		Modified Tree	
	ETX	Hopcount	ETX	Hopcount	ETX	Hopcount
5	1.458929	8.448095	1.423214	7.271429	1.746667	7.498889
10	1.717581	8.921101	1.925988	6.958256	2.598836	7.397041
15	2.66221	8.616179	2.732278	7.181298	3.599875	7.496282
20	3.553829	8.762026	3.621808	7.318304	5.481067	7.622614
25	3.829605	8.515261	4.593671	7.039928	6.195419	7.337402
30	4.771368	8.494829	5.385474	7.194994	7.379986	7.41784
35	6.018755	8.53981	6.104259	7.049731	9.174888	7.231756
40	6.263238	8.858725	6.957644	6.955724	10.30798	7.100279
45	7.549022	8.746565	7.752604	7.255009	11.91198	7.246248
50	7.952004	8.608397	9.329861	7.119143	13.98982	7.187054

Table 4.1: Results obtained for Tree, Modified Tree and Ring Topology for MRP protocol using Dijkstra's Algorithm

4.5 Conclusion

This chapter presented the results and observations obtained for the three topologies i.e. Tree, Modified Tree and Ring Network for MRP protocol using Dijkstra's Algorithm. The Tree Topology and the Modified Tree Topology are seen to be performing better than the Ring Topology when the Hop Count is taken into account which makes them a better topology considering the Energy Constraints of the mobile nodes. But Ring Topology is performing better than both the other topologies when Expected Transmissions Count (ETX) is taken into account which makes it a more efficient topology. In the next chapter, we shall see the fault tolerance capabilities of the three topologies when certain mobile nodes break down.

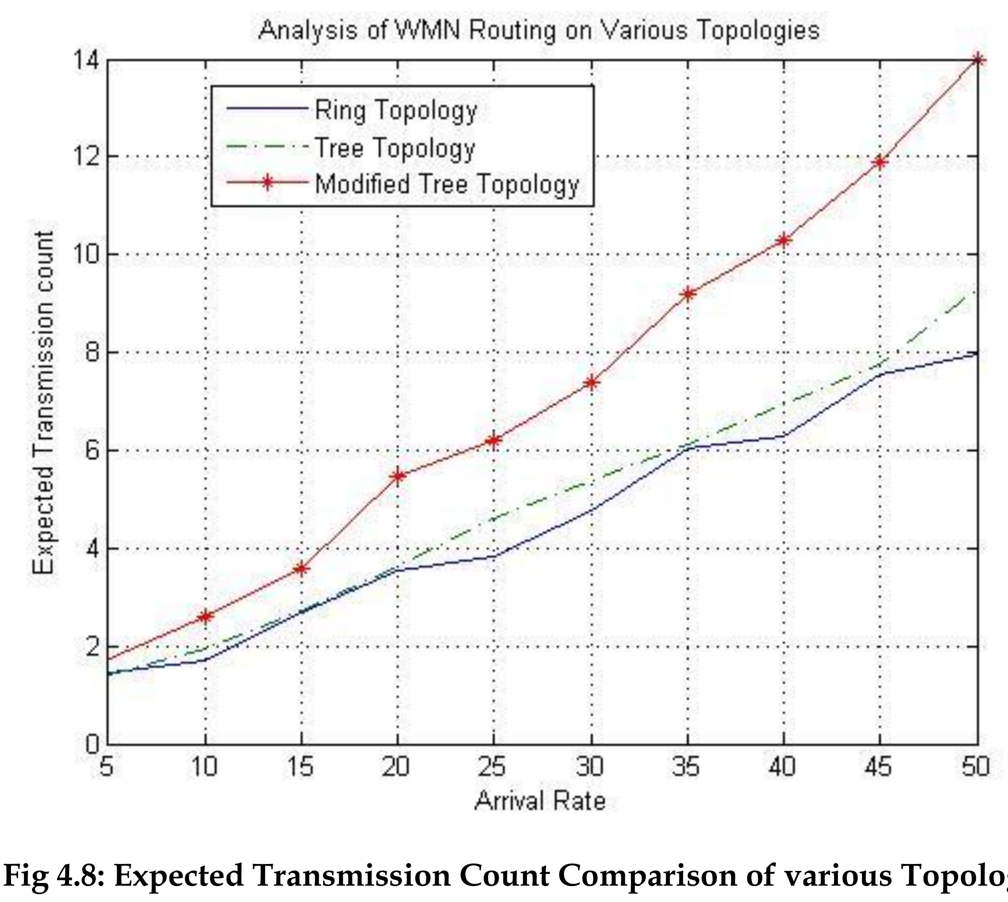

Fig 4.8: Expected Transmission Count Comparison of various Topologies

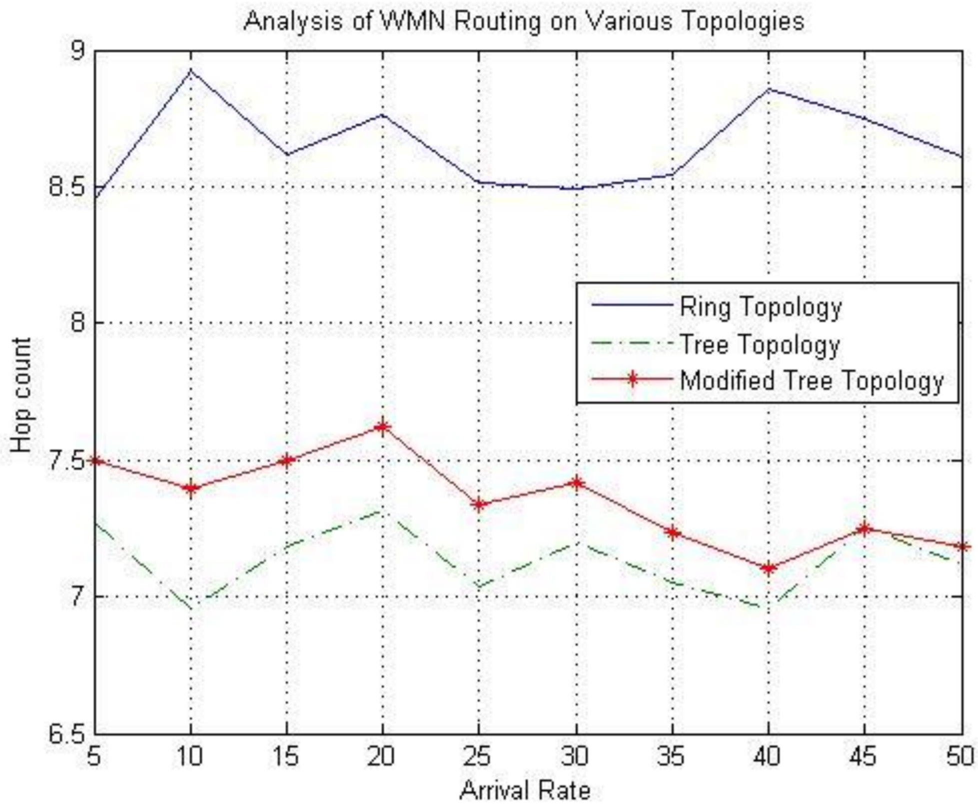

Fig 4.9: Hop-count comparison of various Topologies

Chapter

5 Fault Tolerance in Different Topologies

5.1 Introduction

In the previous chapter, Hopcount and Effective Transmission Count (ETX) for the three topologies, Tree, Modified Tree and Ring were studied and compared. Hopcount can be described as a performance metric for judging the energy requirement from the setup and mobile nodes. In the same way, ETX can be used to compare the efficiency of data transmission. But none of it accounts for the fault tolerance of the system due to failure of nodes or links. In this chapter we shall look into a few algorithms available for topology reconfiguration during node failure to make the system fault tolerant. The main task in topology reconfiguration is the selection of the Leader from among the available nodes. We shall see how different algorithms select the leader and compare their complexities.

5.2 Fault Tolerance through Leader Selection

When nodes first enter into the network and under a router, a Leader selection is done. A node fails, it sends a message to its regarding its failure. The router then executes the Leader selection process on the rest of the nodes to make the system fault tolerant. The Leader selection process is extremely important for WMN as the nodes are mobile and thus this process may be executed many a times making it of prime importance that the process be for least complexity possible.

5.2.1 Leader Selection in Tree and Modified Tree Topology

There are many algorithms for Leader selection in a Tree topology from which one is described below. The algorithm selects the processor with the least identifier as the leader. The algorithm is executed in two phases. In the first phase, identifiers flow in from the external nodes of the tree. Each node keeps track of the minimum identifier l received from its neighbors, and after receiving identifiers from all but one neighbor sends identifier l to that neighbor. At some point, a node receives identifiers from all its neighbors. This node, which is called the accumulation node, identifies the leader. Once the leader is identified, the accumulated node broadcasts the identifier of the leader node to the external nodes. In the case of a "tie" condition (two adjacent nodes having become accumulation nodes) they broadcast their respective "halves" of the tree [40].

```
ALGORITHM:
Input: The unique identifier, id, for the processor running this algorithm
Output: the smallest identifier for a processor in the tree
Let d be the number of neighbors of processor id    {d ≥ 1}
m<--0                                               {counter for messages arrived}
l<--id                                              {tentative leader}
repeat
        {begin a new round}
        for each neighbor j do
                check if a message from processor j has arrived
                if a message M=[Candidate is i] from j has arrived then
                        l<--min (i,l)
                        m<--m+1
        until m ≥ d-1
        if m=d then
                M<--[Leader is l]
                for each neighbor j ≠ k do
                        send message M to processor j
                return M                            {M is a "leader is " message}
        else
```

```
                M<--[Candidate is l]
                send M to neighbor k that has not sent a message yet
repeat
        {begin a new round}
        check if a message from processor k has arrived
        if a message from k has arrived then
                m<--m+1
                if M=[Candidate is i] then
                        l<--min (i,l)
                        M<--[Leader is l]
                        for each neighbor j do
                                send message M to processor j
                else
                        {M is a "leader is" message}
                        for each neighbor j ≠ k do
                                send message M to processor j
until m=d
return M                                        {M is a "leader is" message}
```

Fig 5.1 Leader Selection Algorithm in Tree Topology

5.2.2 Leader Selection in Ring Topology

There are various algorithms for Leader selection in a Ring topology from which one is described below. The algorithm selects the processor with the least identifier as the leader. The challenge is that in a ring there is no obvious place to start. So, computation is started everywhere. At the beginning of the algorithm each processor sends its identifier to the next processor in the ring. In the subsequent rounds, each processor performs the following computations:

1. Receive an identifier i from its predecessor in the ring
2. Compare i to its identifier
3. Send the minimum of these two values to its successor in the ring [40]

If a processor ever receives its own identifier from its predecessor then this processor knows that it must have the smallest identifier and hence, it is the leader. This processor can then send a message around the ring informing all the other processors that it is the leader.

ALGORITHM:

Input: The unique identifier, id, for the processor running this algorithm.

Output: The smallest identifier of a processor in the ring

```
M<--[Candidate is id]
Send a message M to the successor processor in the ring
done<--false
repeat
        Get a message M from the predecessor processor in the ring
        if M=[Candidate is i] then
                if i=id then
                        M<--[Leader is id]
                        done<--true
                else
                        m<--min(i,id)
                        M<--[Candidate is m]
        else
                {M is a "leader is" message}
                done<--true
        Send a message M to the next processor in the ring
until done
return M                    {M is a "leader is" message}
```

Fig 5.2 Leader Selection Algorithm in Ring Topology

5.3 Comparison

For the selection of Leader in the Tree and Modified Tree topology with n nodes and with diameter D, algorithm performs election with O (n) message complexity.

For the selection of Leader in the Ring topology with n nodes identifiers and no distinguished leader, the algorithm finds a leader in n using O (n^2) messages. Moreover the message complexity of the algorithm is O (n^2).

5.4 Conclusion

From both algorithms and their parameters studied above, it is evident that Tree and Modified Tree Topology are better suited for a faulty system as they have smaller complexity for reconfiguration than Ring Topology. Thus Tree and Modified Tree Topology can be called as more fault tolerant than the Ring Topology.

Chapter

6 Conclusion and Future Work

6.1 Conclusion

The path finding problem can be solved in various approaches, among them, Mesh Routing Protocol (MRP) can be used to route the packets with a defined Tree topology of the mobile nodes in the Mesh Network.

In this thesis, we have implemented the Tree Topology, the Modified Tree Topology and the Ring Topology to the Mesh Routing Protocol. The modification in the Tree Topology is to have only one mobile node in each level have child nodes .In the Ring topology one mobile node is directly connected to the router and performs the task of a monitor in that small network. The performances of all the topologies with MRP are studied with respect to the Hopcount, Expected Transmission Count and the fault tolerance of the small networks in case of node failure. The Tree topology performed better than the Modified Tree and Ring topology with respect to the hopcount. The Tree and the modified Tree topology are more fault tolerant than the Ring topology. But the Ring topology performed better when expected transmission count is taken into consideration. The performance of all the topologies is given in the table-4.1. All the results have been obtained to a set of Poisson distribution of requests.

6.2 Future Work

In this thesis report, the path finding problem in Wireless Mesh networks is solved using Mesh Routing Protocol. The algorithm with Tree Topology of mobile nodes is successful in terms of average number of hopcounts for the requests made and the fault tolerance of the system. The problem is analyzed and solved by considering the parameters: Number of hopcounts required, Expected Transmission Count and the Fault tolerance of the each network topology.

The algorithm is proved to be better with a Ring topology with respect to Expected Transmission Count. In future, the performance of the algorithm can be evaluated under various parameters. The performance of this algorithm can be compared with the other algorithms such as SrcRR and PWRP. The algorithm has to be verified for different real-time traffic trends. A mathematical equation may also be tried to be formed to take into account a set of performance metrics so as to evaluate the performance of all the routing protocols in a more holistic manner.

References

[1] Ye Yan, Hua Cai and Seung-Woo Seo, "**Performance Analysis of IEEE 802.11 Wireless Mesh Networks**", Communications, 2008. ICC '08. IEEE International Conference. Publication Date: 19-23 May 2008.

[2] Campista M.E.M, .Esposito P.M. , Moraes I.M., Costa L.H.M., Duarte O.C.M. Passos D.G., de Albuquerque C.V.N., Saade D.C.M., Rubinstein M.G., "**Routing Metrics and Protocols for Wireless Mesh Networks**", IEEE. Publication Date: Jan.-Feb. 2008

[3] Akyildiz I.F., Xudong Wang. "**A survey on Wireless Mesh Networks**", Communications Magazine, IEEE. Publication Date: Sept. 2005.

[4] Sonia Waharte, Raouf Boutaba, Youssef Iraqi and Brent Ishibashi, "**Routing protocols in wireless mesh networks: challenges and design considerations**", Multimedia Tools and Application. Volume 29, Issue 3, Pages: 285 – 303, Year of Publication: 2006, ISSN:1380-7501

[5] Tzu-Chieh Tsai and Sung-Ta Tsai,"**A Cross Layer Routing design for multi interface Wireless Mesh Networks**", Dept. of Computer Science, National Chengchi Univ., Taipei, 15 April 2009.

[6] Jangeun Jun and Mihail L. Sichitiu, "**MRP: Wireless Mesh Networks routing protocol**", Computer Communications, Volume 31, Issue 7, 9 May 2008, Pages 1413-1435.

[7] Daniel Aguayo, John Bicket and Robert Morris, "**SrcRR: A high throughput routing protocol for 802.11 Mesh Networks**", Association for Computing Machinery

[8] Tzu-Jane Tsai and Ju-Wei Chen, "**IEEE 802.11 MAC protocol over Wireless Mesh Networks: Problems and Perspectives**", Advanced Information Networking and Applications, 19th International Conference, 28-30 March 2005, Volume 2, Pages 60-63, ISSN: 1550-445X, ISBN: 0-7695-2249-1.

[9] Rozer E, Seshadri J, Mehta Y, Lili Qiu, Univ. of Texas, "**Simple opportunistic routing protocol for Wireless Mesh Networks**", Wireless Mesh Networks, 2006, WI Mesh 2006, 2nd IEEE Workshop, 25-28 Sept. 2006, Pages 48-54, ISBN: 1-4244-0732-X.

[10] Wellons J, Yuan Xue, Dept. of Electrical Eng. & Computer Sci., Vanderbilt Univ., Nashville, TN, "**Oblivious Routing for Wireless Mesh Networks**", IEEE International Conference, 19-23 May 2008, Pages 2969-2973, ISBN: 978-1-4244-2075-9.

[11] Liang Dai, Yuan Xue, Bin Chang and Yi Cui, Vanderbilt Univ., Nashville, "**Throughput optimization routing under uncertain demand for Wireless Mesh Networks**", IEEE International Conference, 8-11 Oct. 2007, Pages 1-11, ISBN: 978-1-4244-1455-0.

[12] Ganapathy V R, Zakaria M S, Muhammad M, Salleh N M, Johal M S, Abdul Aziz M Z A and Ahmad M R, "**Network and medium access control (NET-MAC) layers for Wireless Mesh Networks (WMN)**"Asia-Pacific Conference, 4-6 Dec. 2007, Pages 1-5, ISBN: 978-1-4244-1434-5.

[13] Siddiqui M S, Amin S O and Choong Seon Hong, "**An efficient Mechanism for Network Management in Wireless Mesh Network**", Advanced Communication Technology, 2008, ICACT 2008, 10th International Conference, Volume 1, 17-20 Feb. 2008, Pages 301-305.

[14] Tsai-Wei Wu, Hung-Yun and Hsieh, “**Interworking Wireless Mesh Networks: Problems, performance characterization and perspectives Source**”, Journal of Parallel and Distributed Computing, Volume 68, Issue 3 (March 2008), Pages 348-360, ISSN: 0763-7315.

[15] Panlong Yang and Guihai Chen, “**Re-match: A Two stage Dynamic Scheduling Algorithm on Wireless Mesh Network**”, HPCC’08, 10th IEEE International Conference, 2008, Pages 486-491.

[16] Y F Ko, M L Sim and M Nekovee, “**Wi-Fi based broadband wireless access for users on the road Source**”, BT Technology Journal, Volume 24, Issue 2 (April 2006), Pages 123-129, ISSN: 1358-3948.

[17] Li-Ping Tung, Wei-Kuan Shih, Te-Chung Cho, YS Sun and Meng C. Chen, “**TCP Throughput Enhancement over Wireless Mesh Networks**”, Communications Magazine, IEEE In Communications Magazine, IEEE, Vol. 45, No. 11.

[18] Chunlei Liu, Fangyang Shen and Min-Te Sun, “**A Unified TCP Enhancement for Wireless Mesh Networks**”, Parallel Processing Workshops, 2007, ICPPW 2007, International Conference, 2007, Pages 71-71.

[19] Zongwu Ke, Layuan Li, Qiang Sun and Nianshen Chen, “**A QoS Multicast Routing Algorithm for Wireless Mesh Networks**”, Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing, 2007, SNPD 2007, 8th International Conference, Volume 1, 2007, Pages 835-840.

[20] Yong Huang, Gaderi M, Towsley D, Gong W, "**TCP Performance in coded Wireless Mesh Networks**", Sensor, Mesh and Ad Hoc Communications and Networks, 2008, SECON'08, 5th Annual IEEE Communications Society Conference, 2008, Pages 179-187.

[21] Hong Fei and Bai Yu, "**Performance Evaluation of Wireless Mesh Networks with Self Similar Traffic**", Wireless Communications, Networking and Mobile Computing, 2007. WiCom 2007. International Conference, 2007, Pages 1697-1700.

[22] Waharte S., Ishibashi B.; Boulaba R. and Meddour D., "**Performance study of Wireless Mesh Networks Routing Metrics**", Computer Systems and Applications, 2008, AICCSA 2008, IEEE/ACS International Conference, 2008 , Pages: 1100 – 1106.

[23] Pirzada A.A., Portmann M, "**High Performance AODV Routing for Hybrid Wireless Mesh Networks**", Mobile and Ubiquitous Systems: Networking & Services, 2007, MobiQuitous 2007. Fourth Annual International Conference, 2007, Pages: 1 – 5.

[24] Jane-Hwa Huang, Li-Chun Wang and Chung-Ju Chang, "**Wireless Mesh Networks for Intelligent Transport Systems**", Systems, Man and Cybernetics, 2006. SMC '06. IEEE International Conference, Volume 1, 2006, Pages 625-630.

[25] Muhammad M., Salleh N.M., Zakaria M.S., Gannapathy V.R., Husain M.N., Ibrahim I.M., Johal M.S., Ahmad M.R., Aziz M.Z.A.A., "**Physical and MAC Cross Layer Design for Wireless Mesh Networks**", Applied Electromagnetics, 2007, APACE 2007, Asia-Pacific Conference, 2007, Pages 1-5.

[26] Jane-Hwa Huang, Li-Chun Wang, Chung-Ju Chang, "**Coverage and Capacity of a Wireless Mesh Network**", Wireless Networks, Communications and Mobile Computing, 2005 International Conference, Volume 1, 2005, Pages 458-463.

[27] Xiaoli Xiao, Min Huang and Weiping Zhang, "**Research and Improvement on Expected Throughput Metric in Wireless Mesh Network**", Young Computer Scientists, 2008, ICTCS 2008, The 9th International Conference, 2008, Pages 605-609.

[28] Lili Qiu, Paramvir Bahl, Ananth Rao and Lidong Zhou, "**Troubleshooting Wireless Mesh Networks**", ACM SIGCOMM Computer Communication, Volume 36, Issue 5 (October 2006), 2006, Pages 17-28, ISBN: 0146-4833.

[29] E Amaldi, A Capone, M Cesana, I Filippini and F Malucelli, "**Optimization models and methods for planning wireless mesh networks**", Computer Networks, The International Journal of Computer and Telecommunications Networking, Volume 52, Issue 11 (August 2008), Pages 2159-2171, ISSN: 1389-1286.

[30] Lili Qiu, Yin Zhang, Feng Wang, Mi Kyung Han and Ratul Mahajan, "**A general Model of wireless interference**", International Conference on Mobile Computing and networking, 13th Annual ACM International Conference, 2007, Pages 171-182, ISBN: 978-1-59593-681-3.

[31] Krishna Ramachandran, Irfan Sheriff, Elizabeth M. Belding and kevin Almeroth, "**A Multi-radio 802.11 Mesh Network Architecture**", Mobile Networks and Applications, Springer Publications, Volume 13, April 2008, Pages 132-146.

[32] Liang Dai, Yuan Xue, Bin Chang, Yanchuan Cao and Yi Cui, "**Optimal Routing for Wireless Mesh Networks with Dynamic Traffic Demand**", Mobile networks and Applications, Springer Publication, Volume 13, April 2008, Pages 97-116.

[33] Subramanian A P, Buddhikot M M, Miller S, "**Interference aware routing in multi radio Wireless Mesh Networks**", Wireless Mesh Networks, 2006, WiMesh 2006, 2nd IEEE Workshop, 2006, Pages 55-63.

[34] IEEE 802.11 http://grouper.ieee.org/groups/802/11/.

[35] Korcak O, Kaya I, Calikh H G and Alagoz F, "**Performance Evaluation of Adaptive and Static Routing Algorithms and Contention resolution techniques in LEO satellite constellations**", Recent Advances in Space Technologies, 2005, 2nd International Conference, 2005, Pages 207-212.

[36] Yaling Yang and Jun Wang, "**Design Guidelines for Routing Metrics in Multihop Wireless Networks**", INFOCOM 2008, The 27th Conference on Computer Communications, IEEE, 2008, Pages 1615-1623.

[37] D S J Couto, D Aguayo, J Bicket and R Morris, "**Path Metric for Multi-Hop Wireless Routing**", In *MOBICOM*, 2003.

[38] Pedro Miguel Esposito, Miguel elias M. Campista Igor M. Moraes, Lu´ıs Henrique M. K. Costa, and Otto Carlos M. B. Duarte, "**Implementing The Expected Transmission Time Metric for OLSR Wireless Mesh Networks**", Universidade Federal Do Rio de Janeiro, Rio de Janeiro Brazil

[39] C. Emre Koksal, Patrick Thiran, Emre Telatar and Hari Balakrishnan**," Effective Number of Transmissions: A Perspective on Time-Varying Wireless Networks**", School of Computer and Communication Sciences - EPFL ,Computer Science and Artificial Int. Lab. – MIT

[40] http://www.dcg.ethz.ch/lectures/fs09/distcomp/lecture/leader.pdf, Leader Selection.