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Routing Optimization and Bandwidth Allocation in Wireless Mesh Networks

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A thesis submitted for the requirements of the degree of Master of Science \ Computer Science

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Abstract

Wireless Mesh Networks (WMNs) are a special kind of wireless ad-hoc networks. It is used to provide mesh users with wireless broadband internet access. The purpose of this thesis is to study the routing protocols used for WMN and investigate the possibility of optimizing the overall WMN network performance by improving the routing process. There are three types of routing protocols used in WMNs, namely proactive routing, reactive routing, and hybrid routing protocols. In this research, we will consider load balancing as the primary tool to provide optimum bandwidth allocation for WMNs. Proactive routing protocols impose a large overhead on the wireless network to establish and maintain routes, which consumes the valuable network bandwidth. On the other hand, the overhead of reactive protocols is much less although it provides a little bit more delay in establishing the required routes on demand. Consequently to get optimum bandwidth allocation we concentrate the present research on reactive routing protocols. The AODV that is a common reactive protocol selected to study the WMN performance under different operating conditions.

In particular, the present research will concentrate on studying the effect of using load balancing in the routing process on the overall network performance. This technique allows evenly distributing the network traffic over the existing wireless links. Two different WMN scenarios are simulated one that provides load balancing and the other does not. The simulations are carried out using the OPNET Modeler simulator package which inherently includes the considered AODV routing protocol. Results are obtained for the cases of low load and high load. There are twelve different scenarios used to evaluate the performance of the mesh network in each case. It has been confirmed that the network performance at high load conditions under load balancing is superior to that for a no load balancing case. In the simulation experiments we relied on the inherent load balancing feature provided by the simulated routers when there is more than one route to the destination, all having the same cost.

The research is extended to propose some ideas to improve and optimize the operation of the AODV protocol. First we suggest to preset an upper threshold for the buffer size in the routers. Routers will refuse to accept new routing requests if there buffers are filled up to a specified threshold, and the requesting router must look for another route. The second proposal is to impose load balancing and select the best route using the fuzzy logic technique. This proposal is checked by two simple examples to verify its validity. It is found to be promising in selecting the best route based on the instantaneous values of three operational parameters, namely the wireless signal strength, hop count and the buffer utilization in the next hop router.

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This research has taken a lot of time, heavy workload in designing, development, optimization, and implementation. There are a lot of difficulties and obstacles I faced, so I want to take this opportunity to pass my heartfelt thanks to all people who helped me and make me able to overcome the difficulties ultimately successful completion of research and solve research problems. My especially heartfelt thanks to my supervisor Dr. Vijeyananthan Thayananthan and my especially heartfelt thanks to co-supervisor Prof. Dr. Mohamed Ashraf Ismail Madkour for guidance, support, and providing advice and direction throughout this research, my heartfelt thanks to friends and teachers who gave me full support. Finally, I thank my father and mother. My heartfelt thanks to friends for their continued support and listen when I needed to discuss the challenges I encountered. My especially heartfelt thanks to Software Systems For Technical Solutions Company because they gave me a good opportunity to apply my research hypothesis and converted my research to technical solutions which are sold in local markets to provide companies by Internet services and connect companies branches together as LAN using mesh network technology. This thesis research is dedicated to my father and mother who give me full support to complete my higher education.

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Acronyms

WMNs	Wireless Mesh Networks
OPNET	Optimized Network Engineering Tool
AODV	Ad-hoc On-Demand Vector
DSR	Dynamic Source Routing
OLSR	Optimized Link State Routing
DSDV	Destination Sequence Distance Vector Routing Protocol (DSDV)
LAN	Local Area Networks
MANETs	Mobile Ad-hoc Networks
WLAN	Wireless Local Area Network
RF	Radio Frequency
AP	Access Point
SSID	Service Set Identifier
QOS	Quality of Service
WANs	Wireless Ad-hoc Networks
MAC	Medium Access Control

IP	Internet Protocol
TCP	Transmission Control Protocol
RREQ,	Routing Request
RREP	Routing Reply
CPU	Central Processing Unit
IFQL	Interface Queue Length
FTP	File Transfer Protocol
RTS	Request To Send
CTS	Clear To Send
TC	Topology Control
LB	Load Balancing
MBLB	Moving Boundary-Based Load Balancing
PHLB	Partitioned Host-Based Load Balancing
PSLB	Probabilistic Striping-Based Load Balancing
LI	Load Index
RC	Routing Cost

Chapter1

Introduction

1.1 Introduction

Wireless communication networks are implemented and managed using radio frequency (RF) communication. In recent days wireless technology has been very popular because its features to bring Internet connectivity and wireless access to network services. Resources for users anytime and from anywhere cover by wireless signal, and make them free from using cable. Wireless devices prices such as access points, routers, and bridges recently were cheap and were easy to setup and configurations. In order to add, the number of wireless devices owned by users such as smart phones, laptops, etc. increased. The use of wireless networks will be necessary because where we go, we need these types of networks to communicate with other people. To browse Internet and use network, resources allow companies to extend their local area networks (LANs). There are many types of wireless networks, and WMN is one of them, it is a particular type of Ad-hoc networks. In general, WMN used as broadband Internet access because its features such as dynamic self-organizing, self-configuring, self-managing and self-healing. Typically the major components of WMN are mesh routers, mesh clients and gateways, mesh routers. They form the backbone of the WMN where mesh routers communicate with each other and form a backbone network which forwards the traffic from mesh clients to the Internet. The router that is directly connected to the internet is called a gateway, and WMN has at least one gateway. Routing process in WMN has very important function which is the heart of the mesh network because it is used to establish the main route between source node and destination node. These nodes used to send and receive data traffic, and this process should be done in efficient way and quickly in challenging wireless environment. Routing protocols in WMNs are distinguished among reactive, proactive, and hybrid routing protocols. Reactive routing protocol is on demand routing protocol, it computes a route only when it is needed, and this reduce the overhead of broadcasts messages, but increase the latency in sending the first packet. Proactive routing protocol uses routing table. Every node knows the routing path to every node in the mesh network, so there is no latency, but there is overhead of unused routes maintenance and routing updates broadcast messages. Hybrid routing protocol combined with the advantages of reactive routing protocols and proactive routing protocols. [1] WMNs have multiple routing paths between mesh network nodes and gateways, and this feature makes WMNs have flexibility behavior. WMN supports load balancing and fault tolerance, so WMNs more robust against failures. Source node has more than one routing path to the destination, when one path is down source node efficiently will use backup route without needing to establish a new routing path. Multipath routing gives us the opportunity to perform better load balancing. This method will distribute the load between available routes and prevent congestion in routes and mesh nodes. We will try to optimize the routing process and bandwidth allocation in WMN. AODV is selected as a routing protocol; it is reactive routing protocol. We will combine load balancing technique with AODV to optimize the performance of the mesh network and distribute the load between available routes to utilize the bandwidth. We will prevent node overloading by define the maximum load for every node, so when one node reach it is the maximum load it will never accept any new routing request. Fuzzy logic system is used in mesh routers to make a routing decision regarding three constraints hop count, signal strength, and buffer utilization in next router. Every router will check the three parameters before select between available routes, route with high probability to send will be chosen as the optimal route.

1.2 Motivation

Millions of people use Internet service, so we have to insure very good network infrastructure to deliver Internet service. WMN is one of the best types of wireless networks to be used as Internet broadband access because it has technical features such as dynamic self-organizing, self-configuring, self-healing and fault tolerance. The major components of WMN are gateways, mesh routers and mesh clients. Gateways connect directly to Internet mesh routers make a backbone of the mesh network because their function is forwarding the traffic from mesh clients to gateways. In general, every mesh router has more than one wireless interface, so when mesh routers connect to each other they make the mesh network. In WMN, every mesh router has more than one route to the gateway, and the big challenges are selecting between active routes. There are many routing protocols are used in WMN, and all routing protocols are divided into three types: proactive, reactive and hybrid routing protocols. We selected AODV as a routing protocol of my thesis research, and it is reactive routing protocol, and AODV has four types of message RREQ, RREP, hello message and error message. The mesh clients will connect to any one of mesh routers, and every new client will broadcast RREQ to find route to send data. The mesh router will receive RREQ and read the message details if the route to the destination already available in routing table the router easily will establish the main route between the source node and the destination, otherwise it will broadcast the RREQ message again. This process will be repeated until the destination receive the request, and the main route be established. The problem in distance vector routing protocols is selecting the shortest route to the destination with minimum hop count, this will produce overload in some routers and gateways because using some routers and gateways more than others will increase the delay in the mesh network and decrease the throughput in the mesh network, and both will affect the performance of the mesh network. Mesh network is multi hop network, and every mesh router has more than one connection to other mesh routers. Many links give us opportunity to use load balancing technique in the mesh network. This will solve the problem of unbalancing in using some routers and gateways more than others. Mesh network is multi hop network, so the packets will pass through many intermediate nodes some of these intermediate nodes has extra load because its position or its buffer size any more load will make bottleneck in this node, and this will drop a lot of packets. We proposed new method to solve this problem by defining maximum load for every node then the node that reach maximum load will never receive any new requests until its load be decreased. WMN has multiple routes, so every mesh node always will be connected with a network and get on the Internet services in the same time if one of mesh routers has failure or damaged, all coming traffic will be forwarded through other route, these features ensure that mesh clients will never be disconnected. Using another route will continue until the mesh router which has a failure be fixed then the traffic will be distributed again same as before the failure.

1.3 Objective of Thesis

Objective of this thesis research is to study, design, optimize, set up WMN and evaluate the performance of WMN by focusing in the routing process and its challenges. Study the possibility of using load balancing technique in WMN and avoid using overloaded intermediate mesh nodes and routes. AODV was selected as a routing protocol in this thesis. This thesis mainly works to achieve the following objectives:

1. Study the latest WMN technology and recognize the mesh network architecture, mesh devices attribute, mesh links and applications.
2. Study the current mesh network problems, and solve all problems that will prevent me to complete this research.
3. Routing process is a critical process in the mesh network, so we mainly focus in this process to optimize the performance of the mesh network.
4. Improve links utilization by using all available routes as possible.
5. Using load balancing technique in the mesh network to achieve link utilization objective.
6. Study and investigate the latest routing optimization techniques including fuzzy logic and bandwidth allocation which allow us to improve the performance of the WMN.
7. Using Ad-hoc On-demand Distance Vector (AODV) as a routing protocol, study the AODV architecture and propose a new methodology to optimize the performance of AODV.
8. Avoid using overloaded intermediate nodes, gateways or routes by exchange the load information of every mesh node through AODV messages.
9. Using routing metrics to evaluate the performance in WMN.
10. Implement WMN performance evaluation through OPNET simulation to evaluate a new method and find out the optimization and bandwidth allocation.
11. Evaluate the results obtained from the proposed method which will optimize packet delivery ratio, increase throughput, distribute the load between all routing paths and make fault tolerance.

1.4 Related Work

Routing process is the heart of WMN because mesh routers form the backbone of the mesh networks. The function of the routing process is selecting the optimal routing path from the source node to the destination node. Routing process determines the quality of the performance of the mesh network. There are many routing protocols, and many modifications have been done to improve and develop this process. Routing optimization and developing process still continuous. Researchers have done a lot of excellent improvements in this area. Routing optimization in WMN is still an active area for researchers. Many routing metrics for WMNs are used to compute the quality of routing paths such as interference, hop-count, link bandwidth capacity, link quality, Throughput, delay and load balancing. Most of the previous works have developed and improved these metrics to optimize the routing process in WMNs.

[2] Have modified AODV routing protocol and combined the route discovery process with a load balancing technique, and balance the load between multiple gateways. Because WMN throughput capacity does not improve with increasing the number of the gateways nodes if we don't use load balancing technique in the network and balance the load among the gateways. The gateway with a load greater than the defined maximum will reject the RREQ and send a message to the source to use alternative gateway with less congestion. disadvantages of this work are making load balancing only between multiple gateways will reduce overloading the gateway nodes, but no load balancing between multiple routing paths, and this will increase overloading the some routing paths and others will not be used or used but with very low load. Congested gateway will reject the RREQ;Wethink congested gateway should automatically broadcast notification messages to active mesh routers to stop sending RREQs to congested gateway and mesh routers should send the RREQ to less-congested gateway this technique will reduce overloading the gateway nodes. If one congested gateway be less-congested gateway, it should send a notification message to mesh routers to tell them they can now send RREQs to this gateway, a lot of notification messages will also increase the overhead traffic in the network.

[3] Have proposed a Delay-based RREP Routing named DRR to balance the traffic loading among gateways and routing paths. Once the intermediate node receives an RREQ packet, extra information will be added to RREQs such as the load percentage in the intermediate node, delay, hop-count, and the path distance. This information are added before forwarding the RREQ packet to discover the loaded routing paths, and congestion gateway to make balancing between gateways and avoid using loaded path. The DRR is compatible to work with routing protocols in WMNs. This is good work, but the delay time will be very large because calculating process of all these information in every RREQ will need a lot of time, this time will be added to the total time to send RREQ and receive RREP. Also, there is CPU and memory overhead because calculation process, add to this load and congestion in routing paths and gateways will not continue forever, network behavior will change continually so this process will be repeated and

losing a lot of time of CPU, and using memory overhead will be increased. Compute load in gateway nodes and routing paths is different soWethink both should be computed separately and in different methods.

[4] Have presented a way to establish connection between a mesh client and one of the gateways, as fast as possible using Artificial intelligence for routing path optimization, and distribute routing information and routing table updates using mobile agents. Routing protocols should establish a connection of new mesh client with ones of gateways, taking into account link cost and routing path length. They have used artificial neural network, as a primary logic, and mobile agents as secondary to find the shortest WMN routes to establish a connection with one of the gateways. Observation of every established connection should be done all the time and recalculate the routing paths should regularly be run if new routing path was found and this new route is better than used route mesh client should be shifted to new better route, this to realize better QoS and to balance the load among gateways in the network as much as possible.

[5] Have proposed two modules in load balancing scheme in WMN, an initial gateway discovery module, which selects a primary gateway for a mesh router, and a load balancing module that rebalances the load among the gateways. Balancing load across the gateway nodes in WMN is important challenge to be addressed, so the main focus of this research is to build an approach for rebalance the load among gateways. New mesh client will establish a connection with primary gateway, and then if there is another gateway close to mesh client will use it to make load balancing between old gateway and new gateway, all mesh routers have a routes to every gateway node, gateways continuously monitor its queue length during a time if it is high then gateway will send notification message to nodes to avoid use it.

[6] Have proposed method to improve the AODV protocol in mobile ad-hoc networks. The new method was used to find multiple routes between the source node and the destination node using Ant Colony Optimization (ACO). They use mobile agents constantly moving in the network, while movement, agents will collect routing information and update routing tables of nodes. This improvement will reduce the routing overhead, buffer overflow, end-to-end delay and increase the performance and throughput. Also, they proposed a load balancing method that uses all discovered routing paths simultaneously for transmitting data. If one of routing paths between source and destination disconnected, the source will use one of the backup routes.

[7] Have integrated two important components: traffic estimation and routing optimization in WMN framework. Traffic estimation framework to predict future traffic demand based on its historical data using time-series analysis. This process will provide us the mean value of future traffic demand and its statistical distribution. Investigating the optimal routing strategy for WMN

will use traffic demand estimations as inputs to balance the traffic load between routing paths and gateways.

[8] Have formulated routing process in WMN as network optimization problem, and presented a general LP (linear programming) formulation for modeling the problem, they presented optimized algorithm for known traffic demand. Load and delay will happen if all nodes select the shortest routing path, so routing load balancing technique is required to balance the load among gateways because gateways is the source of all incoming traffic and the destination of all outgoing traffic of a mesh network. Proposed algorithm will implement the following steps:

1- Investigate the congestion for each edge.

2- Investigate the traffic on all paths.

3- Investigate the route data by finding lowest congested path.

4- Update the congestion for the edges appeared in this path..

1.5 Problem Statement

Internet network grows so fast and millions of people use it daily. Consequently, we need to make stable infrastructure for communication networks systems for Internet users. Wireless network is required because it makes the Internet users feel free from using of the cable, and use the Internet anytime and anywhere, using wireless technology. There are many applications and services available on Internet network, so we have to prepare wireless network guarantees the quality of service and support survivability. There are many types of wire and wireless networks are used to provide Internet service.Weselected WMN as a research area because its characteristics guarantee quality of service and survivability.

WMNs have three main components, gateways, mesh routers, and mesh clients, and mesh routers form the backbone of the mesh network. Mesh routers are responsible for establishing a connection between mesh clients and gateways using routing protocols algorithms. There are many characteristics to WMNs, one of these features, multiple routes from same source node to same destination node. Multiple routes allow mesh routers to have multiple options to establish a connection between mesh clients and gateways and select one of these paths. There are many challenges and difficulties to solve problems of routing protocols and make routing protocols to establish connection between mesh clients and one of the gateways using the optimal route. Most of the wireless routing protocols select the shortest path to the destination. This procedure will cause many problems such as gateway overloading, and intermediate node overloading, routes overloading. If a lot of network packets are forwarded to the closest gateway, this will produce overloaded gateway as well as the closest route to this gateway will be overloaded too. The nodes that located in the center of the network will be used a lot because closest path will pass through it then this node will have an overload, same thing will happen to closest route. Multiple routes help us to use load balancing technique to use all available routes because load balancing technique will improve the performance of the WMN by distributing the traffic between multiple routes, and it is very important for fault tolerance and survivability.

I define the routing process as a critical process in WMN, and it is the heart of WMN, the problem of this process in WMN is how to select optimal route from multiple routes and use all available routes? There are many routing metrics which play an important role in this process such as route quality, route length, hop count, route capacity, nodes overloading, and interference. Load balancing is very important technique, using it in WMN is possible and will improve and optimize the performance of the mesh network. There are multiple routes, so implementing and using load balancing technique will be easy and useful. We will combine this technique with AODV routing protocol to optimize the routing process and maximize the performance of the mesh network to meet the quality of service and survivability. We will take care about loading in gateways, intermediate nodes, and routes. The final solution should produce WMN without overloading in any intermediate nodes and routes in the mesh network

1.6 Research Questions

In this research we study:

How to enhance routing process performance in WMN? To address this problem, we divided routing process problem into three important research questions:

How to estimate the routing protocol performance, to enhance and optimize the performance and minimize the routing process overhead?

How to estimate the load balancing technique, and study the possibility of using it in WMN to enhance and optimize the performance of the mesh network?

How to combine routing protocol system with load balancing system, and estimate the performance of the mesh network?

How to solve overloading problems in gateway nodes, network nodes, and routes?

1.7 My Hypothesis

The goal of this work is optimizing routing process and bandwidth allocation in the mesh network. Most of routing protocols select the shortest routing path, this causes many problems which affect routing process and minimize the performance of network, gateway nodes overloading, intermediate nodes overloading, and shortest routes overloading. The three problems if we can solve them, the routing process will be optimized, and the performance of the network will be enhanced.

I offered solutions to these problems, distributing the traffic between available routes will solve the problem of using only one route more than others. This will happen if we use load balancing technique. Avoiding using overloaded Intermediate nodes we have to modify the routing table of AODV routing protocol to keep the buffer utilization (Butz) in next router, and use new technique protect overloaded Intermediate nodes and deny any new routing requests through it. We propose to use new variable to define the load percentage in every node and define the maximum load, when every node reach the maximum node should drop any new routing request. We have to modify the routing request message (RREQ) by adding Butz for every node will forward the RREQ by adding its Butz with RREQ packet. The next node will read the message and update its routing table with new value of Butz of previous node, then forward the RREQ message adding its Butz and so on until the RREQ reach the destination. The mesh network is multi hop network and there are more than one routing path from source node to destination node, so RREQ message will reach the destination from different routes so we should use new method to force the destination node to wait some time until all RREQ reach to decide which route is less overload than other regarding to Butz field in every RREQ taking into account latency. The mesh network behavior will change every time so the overloaded nodes will be non-overloaded so how the other nodes will now about this change, we solved this problem by using the same change in the Hello message by adding a new field in Hello message packet for Butz, every node will send the hello message will add its Butz to it, every node receive this message will update the Butz of the previous node.

1.8 Scope of Thesis

This thesis focuses on routing process optimization and bandwidth allocation in WMN, in this thesis AODV routing protocol was used one is proactive routing protocol it is OLSR and the other is reactive routing protocol it is AODV. AODV was selected as a routing protocol in my thesis for study the performance of WMN in terms of delay, throughput and stability. OPNET Modeler 14.5 was used as a simulation to set up mesh network and implement the hypothesis. Combining between AODV and load balancing technique in WMN is the main objective of this research, add to this avoidance of using overloaded intermediate mesh nodes by defining maximum load for every node to prevent bottleneck problem happen in mesh network nodes.

1.9 Research Methodology

Research methodology we used in this research is divided into two parts, theoretical part and simulation part as shown in Figure (1.9.1). In the theoretical part, we will study and understand the WMN and its routing process to find out shortcomings and produce a new method to optimize the routing process and bandwidth allocation in WMN. In the simulation part, we will set up a mesh network using OPNET simulation and implement a new method and run the simulation to collect the results and analysis the results to evaluate the performance of a mesh network.

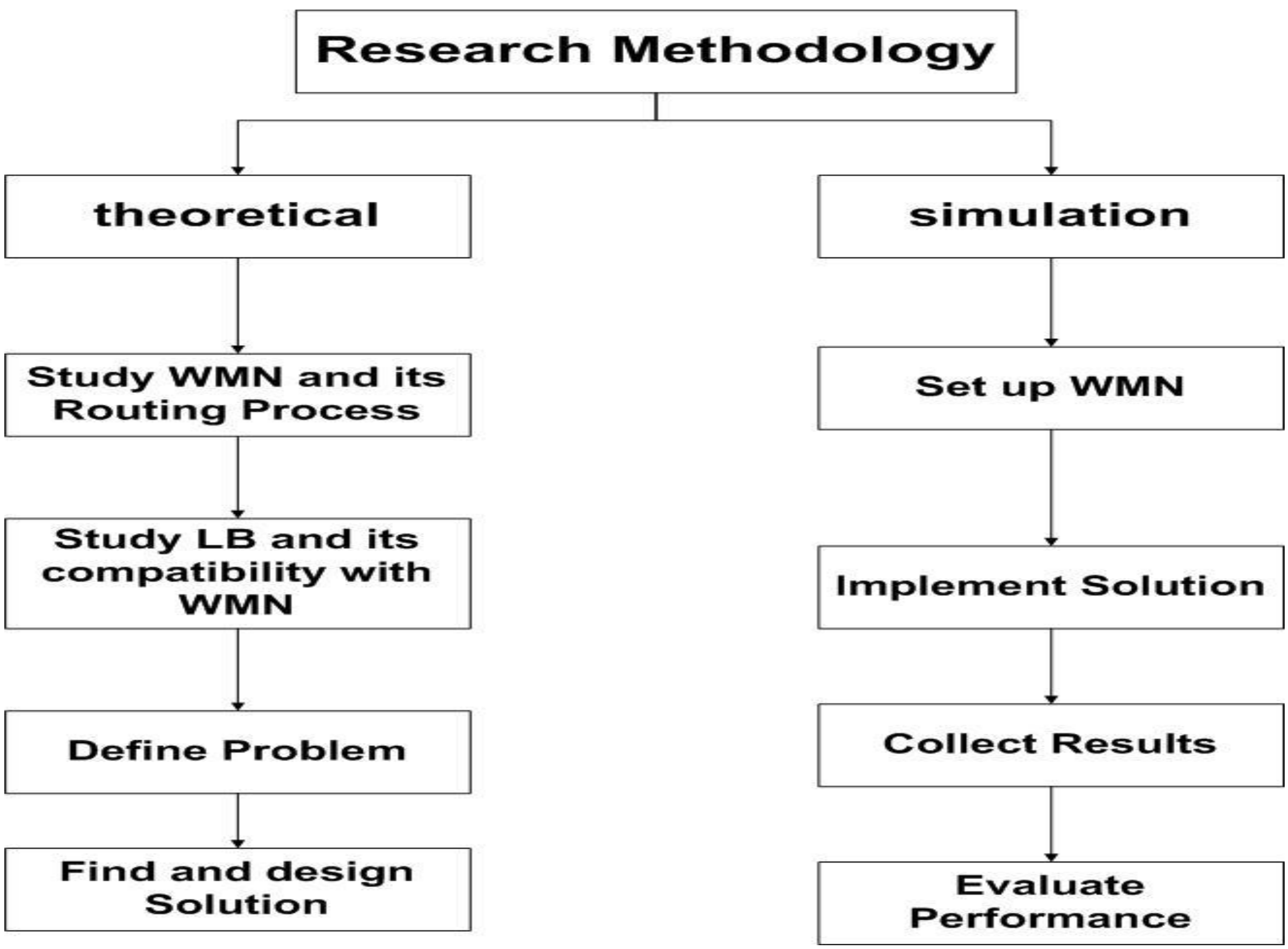

Figure 1.9.1 Research Methodology

1.10 Thesis Organization

This thesis research work is based on routing optimization and bandwidth allocation in WMN, by focusing on combining routing process with load balancing using the best feature of the mesh network that is there are many routes from the source node to the destination node, and prevent node bottleneck because overloading happen. The whole thesis research work is presented in nine chapters that are briefly described as follows:

Chapter – 2, Background: it provides study and review of necessary background information about our thesis research area and provides a literature to know what have been done before in this area.

Chapter – 3, Provides study and review of some routing protocols in WMN and explain how theses protocols work in a mesh network.

Chapter – 4, Provides study and review routing metrics and how to test the performance of routing protocols in WMN to know the best one regarding optimization process.

Chapter – 5, Results and Analysis: it provides study of our results comparative between mesh network scenarios.

Chapter – 6, Discussions of Simulation Analysis: it provides more details about results and Analysis chapter and gives the answers with respect to our thesis research objectives.

Chapter – 7, fuzzy load balancing, it provides the optimization ideas we proposed to get on the best performance and maximize the throughput of the mesh network and avoid nodes overload.

Chapter – 8, Conclusion and Future work: provides what we have learned from this research and did we achieve our objectives, and what did we suggest about research area? The untouched topic in this research will be the future work.

Chapter2

Background

2.1 Overview of Wireless Mesh Networks

Wireless Mesh Networks (WMNs) represent a type of ad-hoc networks. [4] Mesh networks are one of the hot topics for academic and industry researchers because its features and advantages. WMNs are used in general as a broadband wireless Internet access, and sometimes used to extend the coverage area of wireless local area network. [9] WMN can be characterized by many technical features, such as dynamic self-organizing, self-configuring and self-healing features. Typically the major components of WMN are mesh routers, mesh clients and gateways, mesh routers form the backbone of the WMN. Routers communicate with each other and form a backbone network which forwards the traffic from mobile clients to the Internet. [2] The router that is directly connected to the Internet is called a gateway, and WMN has at least one gateway, but WMN usually has more than one gateway, this gives us good opportunity to implement load-balancing between gateways and routing paths, also for fault tolerance if one connection down, the mesh routers will use another routing path to make a connection. Mesh router usually has more than one wireless interface, while mesh clients usually have a single wireless interface, and multiple wireless interfaces allow mesh routers to connect to multiple wireless routers then every router has more than one routing path to forward the routing requests of mobile clients to the closest gateway using wireless mesh routing protocol. The clients could be stationary or mobile and connect to mesh routers to access network service and send the routing requests to mesh routers. WMN infrastructure in figure (2.1.1) was divided into backbone infrastructure and client infrastructure. In backbone infrastructure, mesh routers have links among themselves and provide an infrastructure for the clients that connect to them, and it is easy to integrate WMNs with existing wireless network, through gateway and bridge functionalities in mesh routers. WMNs characteristics make it provide support for a lot of applications in the same time another type of wireless technology can't, example wireless broadband services, high-speed metropolitan area networks, and intelligent transportation systems, etc. Routing process is one of the WMN challenges. Routing is the heart of WMN, and the routing protocols should select the optimal routing path for the source node to the destination node. Routing protocol determines the performance of WMN, and it is the key factor. Routing protocol is responsible for establishing and making a decision to select the optimal routing path regarding link cost calculations, total path length, number of hop, and load in the routing path, this to optimize network performance. [3]. There are common features between ad-hoc networks and WMNs. Routing protocols developed for ad-hoc networks were developed to be used in WMNs. The most used routing protocols in WMNs are Dynamic Source Routing (DSR) and Ad-hoc on-demand distance vector (AODV). Routing process in WMNs is still active research topic, so many researchers try to design new routing protocol or optimize the available routing protocols for WMNs to improve the performance of WMN. [10], [11]

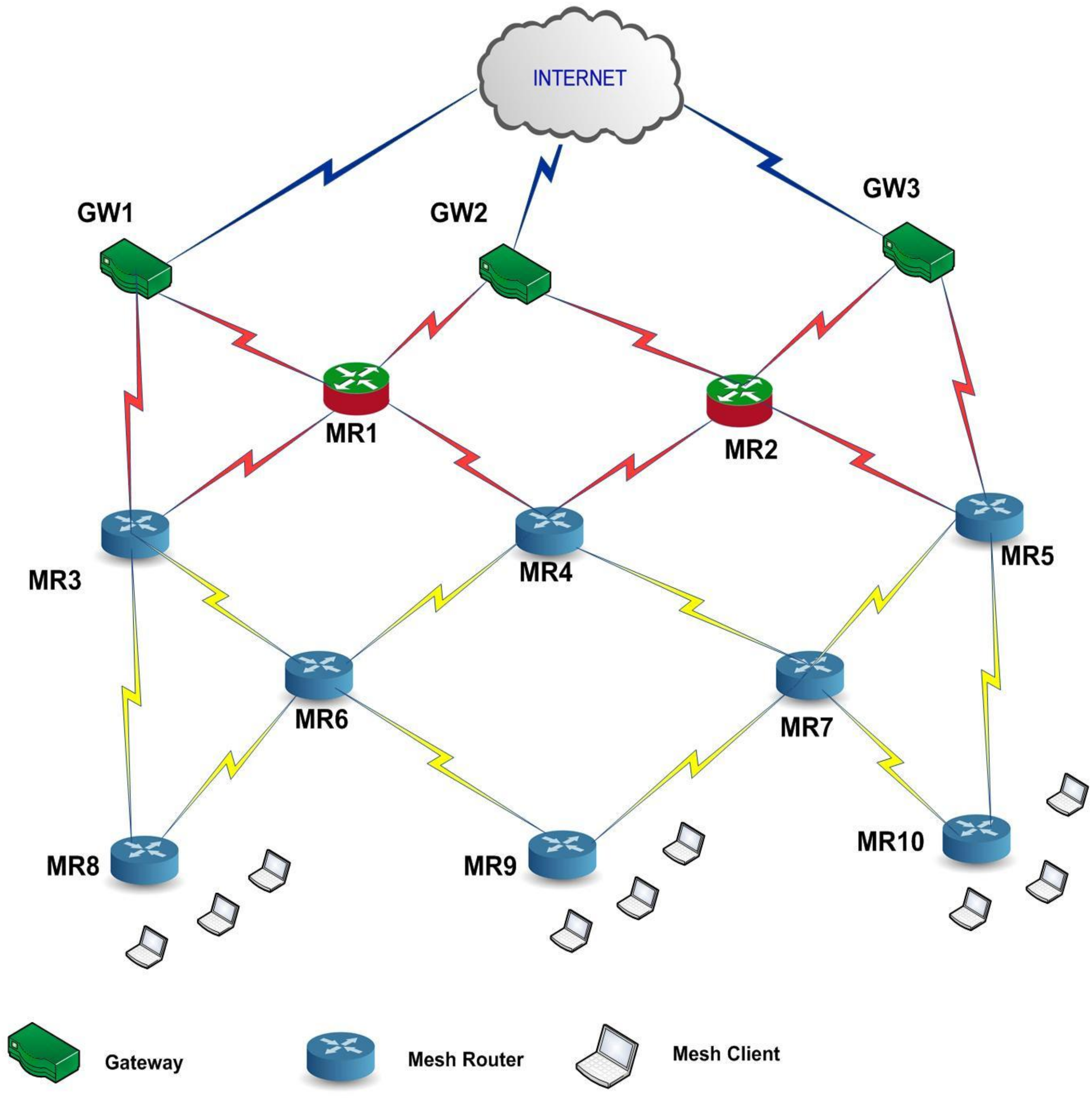

Figure 2.1.1 WMN Architecture

2.2 Network Routing Overview

In a communication networks if one node wants to reach another node, some process is needed to allow one node to reach another node, this action has to be done quickly and efficiently because all nodes in any network need to reach and communicate with another node in network. network routing process, this process allows nodes in a communication networks able to send messages and packets from one node to another by determining the routing path in the network from the sender (source) to the receiver (destination) this process happens efficiently and quickly. The device that does this function is called a router. Moving messages from the source to distention some time pass through intermediate routers until the message reach to the destination. In general, most of communication networks have more than one router, and sometimes the routing path from the source node to the destination node will pass through other routers. Routers in the network should know at least one routing path from the source node to the destination node. Every node in the network will use routing path to communicate with other nodes. Routers in the network has a routing table which contains routing information and all routing paths which will be used to deliver the messages and data from source nodes to destination nodes. Routing table will be updated continuously to make sure that every router has updated routing table with the correct routing paths in the network. Communication in WMNs between nodes happens over multiple wireless hops, so the core functionality of WMNs is routing capability. The main function of routing protocols is the routing path selection between the source node and the destination node in WMNs so that the nodes can communicate over multiple wireless hops this should be done quickly and efficiently with minimum overhead. WMNs share a lot of features with ad hoc networks, the routing protocols that are used in ad hoc networks can be used in WMNs such as Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV), with some modification in routing protocols to meet the requirements of WMNs, designing and developing of routing protocols for mesh networks is still an active research area. [1] In proactive routing protocol, every node has all routing information about other nodes and knows the route to every node in the network. Combining the advantages of reactive routing protocols and proactive routing protocols produced hybrid routing protocols. Routing Protocols in WMNs have to include some features such as fault tolerance, load balancing, reduction of routing overhead, scalability, and support QoS. WMNs support multiple routing path that is why it is more robust against failures. Nodes in the mesh network have multiple routing paths from source to destination, when one path is broken another path is available and easy to be chosen. Using multiple routing paths gives us another objective to implement load balancing technique to prevent congestion among data links and nodes. [12], [13-14], [15]

2.3 Routing in Wireless Mesh Networks

WMNs have many features in wireless communication such as, flexibility, reliability, stability, and high performance. WMN nodes are connected together and communication between mesh nodes over multiple wireless hops. WMN has static and stable infrastructure guarantees quality of services, reliability and high performance. Routing capability is critical area and core function in multihop mesh networks. The main function of routing protocol is how to select routing path between the source node and the destination node with efficient method and short period with minimal routing computation overhead. Routing protocols are used to establish and maintain the main route which is used by mesh nodes in communication over multiple wireless hops, and this process should be done in efficient way and quickly in difficult wireless environment. Mesh nodes work as a router. Data packets are forwarded over multiple wireless hops, and this process is critical and affects in mesh network reliability and network performance especially in the challenging wireless environment. Reactive routing protocol is on demand routing protocol, it computes a route only when it is needed, and this reduce the overhead of broadcasts messages, but increase the latency in sending the first packet. Proactive routing protocol uses routing table, every node knows the routing path to other nodes in the mesh network, so there is no latency, but there is overhead of unused routes maintenance and routing updates broadcast messages. Hybrid routing protocol combined between the advantages of reactive routing protocols and proactive routing protocols. WMNs can use any one of the routing protocols classes described earlier, however, not all routing protocols will work well because every routing protocol depends on the wireless scenario, used applications and the performance requirements.

Routing protocols works in layer 3 in the OSI layer model and the TCP/IP model, but routing protocols in WMNs are developed to work in layer 2. Routing in layer 2 is difficult to implement but there are some benefits such as, faster access, faster forwarding. Routing path selection procedure is the same in layer 2 or layer 3 however, the routing process in layer 2 uses MAC addresses, but in layer 3 uses IP addresses. There are many requirements on Routing process in WMNs, and WMNs routing protocols should capture features such as, fault tolerance, load balancing, reduction of routing overhead, scalability, and support QoS. WMNs have multiple connections between nodes. This feature makes WMNs have flexibility behavior and support load balancing, fault tolerance. WMNs are more robust against failures. The source node has more than one routing path to the destination, when one path is down the source node easily will use backup route without needing to establish a new routing path. Multipath routing gives us good opportunity to implement better load balancing, and this method will distribute the load between available routes and prevent congestion in routes and mesh nodes. [16-19]

Routing metrics is used to determine and optimize the quality of the link between source node and destination node these metrics should be developed and optimized to get on minimum cost in routing path. For example of some existing routing metrics for WMNs, hop count, expected transmission count (ETX), weighted cumulative expected transmission time (WCETT), metric of interference and channel-switching (MIC). [20]

Routing protocols for wireless multihop networks have common concepts, but there are some special routing protocols for mesh networks. Every routing protocol can be extended and modified to work in multihop and multiple wireless interfaces of the mesh network.

2.4 Load Balancing in WMNs

Today, communication networks are used in all digital systems that have some components need to communicate with each other. There are many metrics are used to measure the performance of communication networks, the most common metrics are throughput, latency, and reliability. To achieve the high performance of the network, we focus on the routing process of packets through the communication networks and bandwidth allocation, because both are very critical processes and play very important roles in optimizing the performance of the network.

WMNs are multihop wireless networks with limited resources the two main resources are bandwidth and network capacity. Load balancing technique is critical to optimizing the bandwidth and network resources utilization. It is used to distribute the load between available routes and resources efficiently. Gateways connect the WMN clients to the Internet, and all traffic is routed using multiple hops to the gateway, and reachable gateway over the minimum number of hops will be selected by nodes for external communications. Gateway handles very large number of packets and forwards packets from mesh clients to the Internet and backwards packets from the Internet to mesh clients. Most of wireless routing protocols select the shortest routing path from mesh routers to the Internet gateway, and this will produce congestion, buffer overflow, and packet loss, at the intermediate routers or in the gateway. Hence to improve the performance of the mesh network we have to use all bandwidths of available routes. Bandwidths allocation and utilization can be achieved by using load balancing among WMN gateways and routes. In WMN, using shortest path routing schemes will make some routers which are closer to the network gateway overloaded and exhaust bandwidth, processing power, and memory storage, these nodes with a maximum load become the bottleneck for the load on the entire network.

Load balancing technique provides us many of solutions for multiple WMNs problems such as gateway overloading, center nodes overloading and routes overloading. In general WMNs have multiple gateways with low bandwidth, imbalance of network load among routes and gateways will minimize the performance of the mesh network, so load balancing is very important to be used to distribute the load among gateways and avoid overloading routers and gateways. [2], [5], [21-23]

2.4.1 GATEWAY LOAD BALANCING IN WMNs

There are many gateways load balancing mechanisms are used to distribute the traffic between gateways. The mechanisms are boundary-based load balancing (MBLB), partitioned host-based load balancing (PHLB), and probabilistic striping-based load balancing (PSLB). In MBLB there is a flexible boundary around each of the gateway nodes, nodes in that boundary communicate directly with gateways in the same boundary, the boundary zone is periodically redefined. There are two main approaches under MBLB, shortest path-based moving boundary approach and load index-based moving boundary approach. In first one, every gateway broadcast advertisement packet to neighbors periodically to tell them about its presence. The nodes that receive the gateway announcement packet will use this gateway as its dominator gateway and use it to external communications. If WMN nodes receive more announcement packet from many gateways, node will select reachable gateway over the minimum number of hops.

2.4.2 Load Index-Based Moving Boundary

Load Index-Based Moving Boundary Approach is dynamic load balancing solution. Each gateway broadcasts periodical message packet containing its current load index (LI). Nodes in the mesh network select gateway according to the gateway LI. Then the low loaded gateway will be selected by network nodes, and the high loaded gateway will be selected by few nodes. This solution allows network nodes to leave overloaded gateway and switch to gateways with less LI.

2.4.3 Partitioned Host-Based Load Balancing

In Partitioned Host-Based Load Balancing, WMN nodes grouped to make sets of nodes, there is the gateway in each group, it is similar to the MBLB but there is no clear boundary in PHLB. There are two main approaches in PHLB, centralized host partitioning approach, and distributed host partitioning approach. In the first approach, all load information about all gateway nodes and all traffic requirements of WMN nodes are computed and saved in a central server. The central server responsible for assigning mesh network nodes to suitable Internet gateway, it distributes the nodes load among gateways and ensures that gateways are equally loaded. The load computational process is overhead and very expensive.

2.4.4 Distributed Host Partitioning-Based

In Distributed Host Partitioning-Based Load Balancing, gateways nodes form a logical network to exchange load and traffic information, gateway nodes use wireless links among WMN nodes to form a logical network and periodically exchange load and capacity information between gateways, every node will periodically provide its dominate gateway by its traffic demands.

Loaded gateway can handover a node to another lightly loaded gateway, and there is gateway periodic time interval to run the load check.

In MBLB and PHLB approaches, WMN nodes use only one gateway for external communications. There is a new approach called Probabilistic Striping-Based Load Balancing (PSLB). This approach allows WMN nodes to use simultaneously multiple gateways for external communications. It is a perfect gateway load balancing approach. There are two main approaches under PSLB, all node probabilistic striping and boundary node probabilistic striping approach. In the first approach, every node in WMN will identifies all the gateway nodes in the mesh network and distributes its traffic as parts among gateways. Every gateway node broadcasts its capacity information, and nodes will use this information to decide and estimate what parts of traffic can be sent through each gateway, there is problem in delay time, because each connection between node and gateway has different delay, in a large number of transmissions will need to high packet reordering.

2.4.5 Boundary Node Probabilistic Striping Approach

Boundary Node Probabilistic Striping Approach combined between shortest path-based moving boundary load balancing approach and the probabilistic striping approach. There is the boundary around each WMN nodes at the boundary can utilize available gateway nodes in the same boundary. Gateway nodes broadcast its capacity information, and WMN nodes will use gateways capacity information to decide how to send its traffic among the available gateways in a probabilistic approach. [24]

2.5 Center Loading in WMNs

Center loading is an important issue in WMN. Nodes that are located in the center of the mesh network have overloaded comparing to other nodes in the mesh network. WMN is multihop network, and shortest path routing protocols are the main reasons behind center loading. The best solution to solve these problems is using a technique dynamically determines the load on WMN nodes and forward new traffic through less loaded nodes. There are some schemes to solve this problem such as, every node in WMN sends its traffic and load information to its neighbors, and then neighbor node will decide to select less loaded node as the next hop. Another approach is every node in WMN broadcasts its traffic and load information, and then source routing with load balanced can be easily used. Final approach is the traffic and load information of all WMN nodes should be sent to the central node which will help other nodes in selecting less loaded routes.

2.6 Routing Load Balancing

Routing is the process of finding a path that is used to transmit data from the source node to the destination node in the mesh network. Routing process has two phases, forward phase and backward phase, in the forward phase the source node broadcasts RREQ message to search for a path toward a destination node, backward phases RREP message is sent back from the destination node to the source node. The RREQ packet should contain routing cost (RC), and it presents the traffic load of each intermediate node between source node and destination node, and this field is updated upon moving the packet between intermediate nodes. Then the destination node collects this information of RC to select the path with the minimum routing cost. WMN nodes forward the routing requests to gateways, and the gateways can play a critical role in load balancing by grouping the nodes in multiple non-overlapping groups, these groups will be used in load balancing. Any new node join the network will broadcasts RREQ first gateway receive this request will assigns a group identifier to this node to be a member of the group and send RREP packet with a group identifier back to the source node, if intermediate node receive this RREQ, and this intermediate node is a member of the group it will allow the new node to join the group and send back RREP packet. The figure (2.6.1) shows us simple flow chart of routing load balancing in WMN. [25-26]

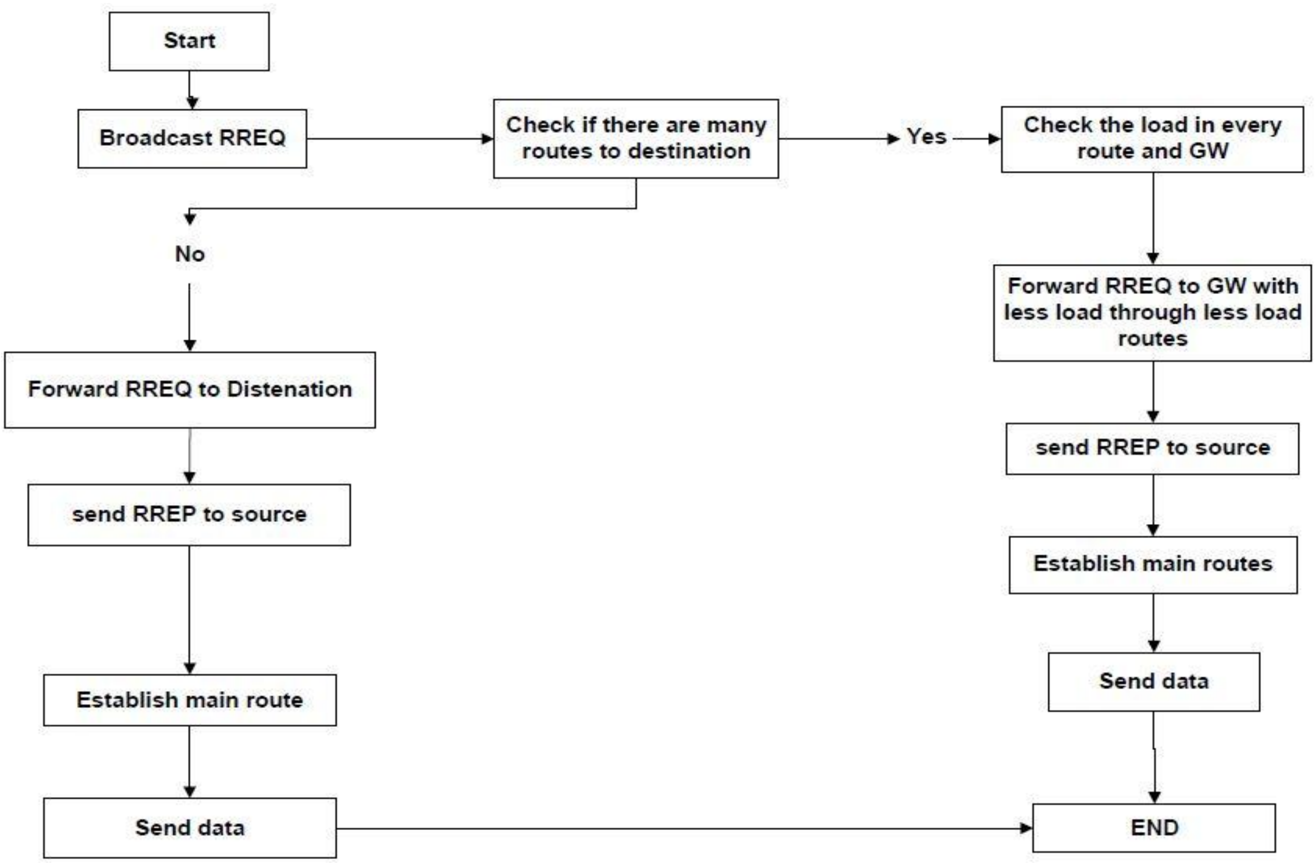

Figure 2.6.1 Routing Load Balancing

2.7 Fuzzy Logic

Fuzzy Logic is used to allow computer systems to make decisions same way that people do, and linguistic terms are used in people thinks, but in computer systems numerical terms are used. For example air conditioning (AC) systems use fuzzy logic system, the speed of AC fan depends on the external temperature or the user temperature which provided by user, so if the external temperature is high the AC will increase the speed of its fan, if the external temperature is medium the speed of AC fan will be medium, and if the external temperature low the speed of AC fan will be very slow and so on.

Fuzzy logic is good tool to be used in making routing decisions in WMNs, because selecting the optimal route among many routes require taking into account many constraints such as interference, bandwidth, hop count, buffer utilization, signal strength, etc. Figure (2.7.1) shows us the main three components of fuzzy logic which are:

1. Fuzzification (Input)
2. Knowledge base (Rules)
3. Defuzzification (Output)

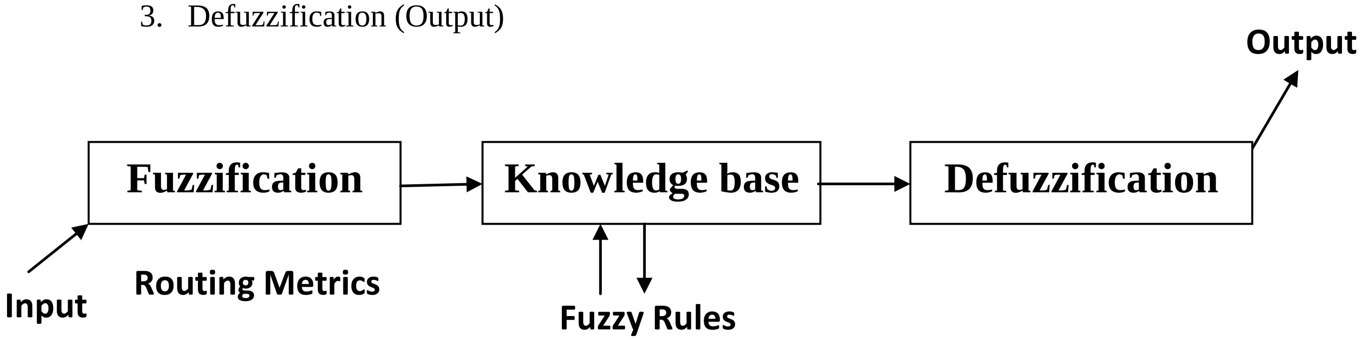

Figure 2.7.1: A block diagram of fuzzy logic system.

Fuzzification step determines degree of membership to input in a fuzzy set for example the inputs in this thesis are signal stregth, hop count, and buffer utilization. The knowledge base rules are used to present the fuzzy relationship between input-output fuzzy constraints using if then rules form for example if the signal stregth is high, buffer utilization is low, and the hop count is low then the probability to send (output) will be high. Final defuzzification step which used to convert the outputs of fuzzy rules into the crisp value. [27-31]

Chapter3

Routing Protocols in WMN

3.1 Routing Protocols for WMNs

Routing protocols in WMNs are distinguished among reactive, proactive, and hybrid routing protocols. Reactive routing protocol is on demand routing protocol, it computes a route only when it is needed, and this reduce the overhead of broadcasts messages, but increase the latency in sending the first packet. Proactive routing protocol uses routing table, every node knows the routing path to other nodes in the mesh network, so there is no latency, but there is overhead of unused routes maintenance and routing updates broadcast messages. Hybrid routing protocol combined between the advantages of reactive routing protocols and proactive routing protocols. WMNs can use any one of the routing protocols classes however, not all routing protocols will work well because every routing protocol depends on the wireless scenario, used applications and the performance requirements. There are different methods in the routing process to deliver and exchange network messages and data packets between network nodes the common three schemes are Broadcast, Multicast, and Unicast.

- Broadcast sends message to all the nodes in same subnet in the network.
- Multicast sends message from one node in the network to many nodes in same subnet in the network.
- Unicast sends message from one node to a special node in the network

3.2 Types of Routing

Every router in the network has a routing table that is used to store all routes to the destination nodes in the network. There are mainly two methods of building a routing table:

- Static Routing
- Dynamic Routing

3.2.1 Static Routing

In static routing method network administrator is responsible to create, update, and maintain the routing table manually. There is static route to every network and this route should be added in every router to insure the full connectivity, but this method will be impractical on large networks, because it is difficult to maintenance all static routes. Static routing method saves network bandwidth and reduces routing overhead because routers don't share routing table information with each other. Static routing doesn't support fault tolerance, so any failure in routing infrastructure manual trace is required to fix the problem.

3.2.2 Dynamic Routing

In dynamic routing method, routing protocols are used to create, update and maintain the routing table, all routers share routing table information with each other using routing protocol. Routing protocols dynamically can select different route if there is any changing in the routing infrastructure. [1], [32], [33]

3.3 Routing Protocols

Routing protocol is the main core of the routing process, and it is used to find a routing path through which packets can be forwarded. Routing protocol allows routers in networks to communicate and exchange routing information. Every routing protocol has a different method in working, and this method depends on used algorithm, so routing protocol is the implementation of routing algorithm. Different matrices are used in routing protocols to select the optimal route which is used to transfer the packet across the network such as hop count, delay, bandwidth ect.

3.3.1 Destination Sequence Distance Vector Routing Protocol (DSDV)

The DSDV is based on the Bellman–Ford algorithm, it is proactive routing protocol, which means it is table-driven routing protocol and all routing information about all WMN nodes is available in routing table, so every node has a route to every destination and what is the next hop to destinations. Updating process happens regularly so any changing in routing information in WMN will be broadcasted to all nodes to update the routing table. DSDV solved the routing loop problem by using a sequence number. DSDV use hop count as a cost metric so the route with less hop count is the shortest route. When one node receive updating with two routes to same destination select greatest destination sequence number if they are equal use routing cost metric (hop count). DSDV routing tables need regular update this is overhead and consume power and wireless bandwidth, also when the network is very big and every node should maintenance all routes to all destinations this is very hard and consume the bandwidth. [15]

3.3.2 Destination Source-Routing Protocol (DSR)

The DSR is a routing protocol for WMNs, and it is reactive routing protocol route is established only if it is needed. RREQ, RREP, and RERR messages are used in DSR, and RREQ is used in route discovery, so when the node need to reach the destination it broadcast RREQ, when the destination receive the RREQ it will send back RREP. DSR doesn't set reverse route in the routing table because RREQ collects the address of the reverse route when it is going to the destination, while RERR is used when there is an error in one route to notify other nodes about this error. DSR routing tables doesn't need regular update, so there is no overhead and no consuming power and wireless bandwidth, but when the network is very big, and every node should establish route to destinations this will produce overhead and delay in the first time of establishing the route. [34]

3.6 Optimized link state routing protocol (OLSR)

OLSR is proactive routing protocol. It is table-driven routing protocol and all routing information about all WMN nodes is available in routing table. Every router has a route to every destination and knows about what is the next hop to the destinations. OLSR uses shortest path algorithm and hop count as a routing metric for computation of route. Broadcast mechanism was reduced by half because using of multipoint relays (MPRs), so every node only broadcast to its neighbors, same thing happens for link state information. In OLSP, every node periodically broadcasts hello messages to check the availability of routes this message has a list of the neighbors of the sending node and some routing information. Link state information is broadcasted through topology control (TC) message which contains a link set, neighbor set, hop neighbor set and topology set, any changing in one of these metrics node should recalculate the routing table and broadcast update to all nodes in WMN. [35]

3.7 Ad hoc On-demand Distance Vector Routing Protocol (AODV)

AODV is a distance vector routing Protocol, and it has been a popular routing protocol for MANETs. It is a reactive (on demand) routing protocol. AODV combine between advantages of Dynamic Source Routing (DSR) routing protocol and Destination-Sequenced Distance-Vector (DSDV) routing protocol, it supports multi-path routing. When one node in the network needs to reach other node, AODV routing protocol will run discovery mechanism to find routes to the destination node and set up the route, main route will be established between source node and destination node and only active routes will be maintained. The advantage of this protocol is minimizing the routing overhead. WMNs have limited wireless bandwidth, so no needs to construct routes if mesh clients do not need because this will waste the bandwidth.

Recently, many adaptations have been proposed in AODV to be compatible with WMNs and meet the requirements of mesh networks. In AODV, every host node has a routing table, it contains route record to each destination node that the host node communicating with it. AODV routing protocol has four phases: route discovery, data forwarding, route maintenance and route revocation.

Routing discovery process is divided into two phases: Route Request and Route Replay as shown in Figure (3.3.4.1). When source node wants to communicate and send data to another node, and there is no active route entry in the routing table to this destination, the source node will broadcast a route request packet to its neighbors and wait for the response of RREP packets. Intermediate nodes will receive RREQ packet and update its routing table. If the intermediate node has an active route to the destination, it will send the RREP packets to the source node otherwise it will broadcast the RREQ again. Broadcasting process for RREQ will be repeated until the RREQ reaches the destination, then the destination node will send the RREP packets to the source node. There is very important task of route discovery, and it is creating a reverse route, and this route will be used by RREP packets to come back to the source node.

In AODV, RREQ packet format in route discovery mechanism contains ID, timeout, hop count, the destination address and sequence number. The RREQ ID is a unique number to ensure that nodes rebroadcast the RREQ only ones and avoid broadcast storms, timeout is associated with routing information to avoid counting to infinity, sequence number to avoid routing loops, hop count indicates to the number of hops that RREQ has traveled through it.

On receipt of RREP packet of the destination node, the source node will create a route to the destination node and update routing table, and source node now be ready to send the data packets to the destination using discovered routing path.

In route maintenance phase, every node periodically broadcast hello messages to its neighbors nodes to check the routes, if available routes are still active routes nothing will happen, but if there is no response in specified time interval from a neighbor node, this mean there is link failure in this route, route error (RERR) message will be broadcasted to all neighbors nodes to update the routing table and remove all unreachable destinations. Nodes should broadcast RREQ packet again to discover a new route instead of removed routes. [36]

In route revocation phase, there is a certain time for routing information in the routing table, if this information not used, it will be removed from routing table.

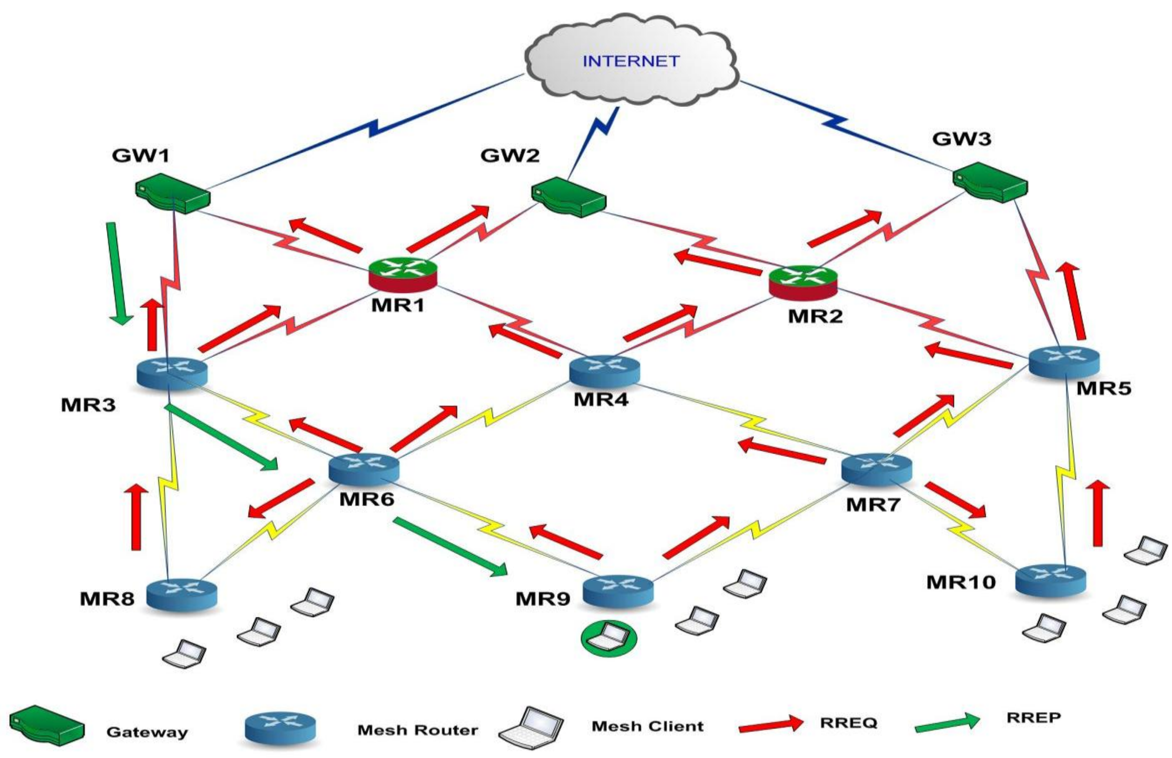

Figure 3.3.4.1 AODV RREQ and RREP Messages.

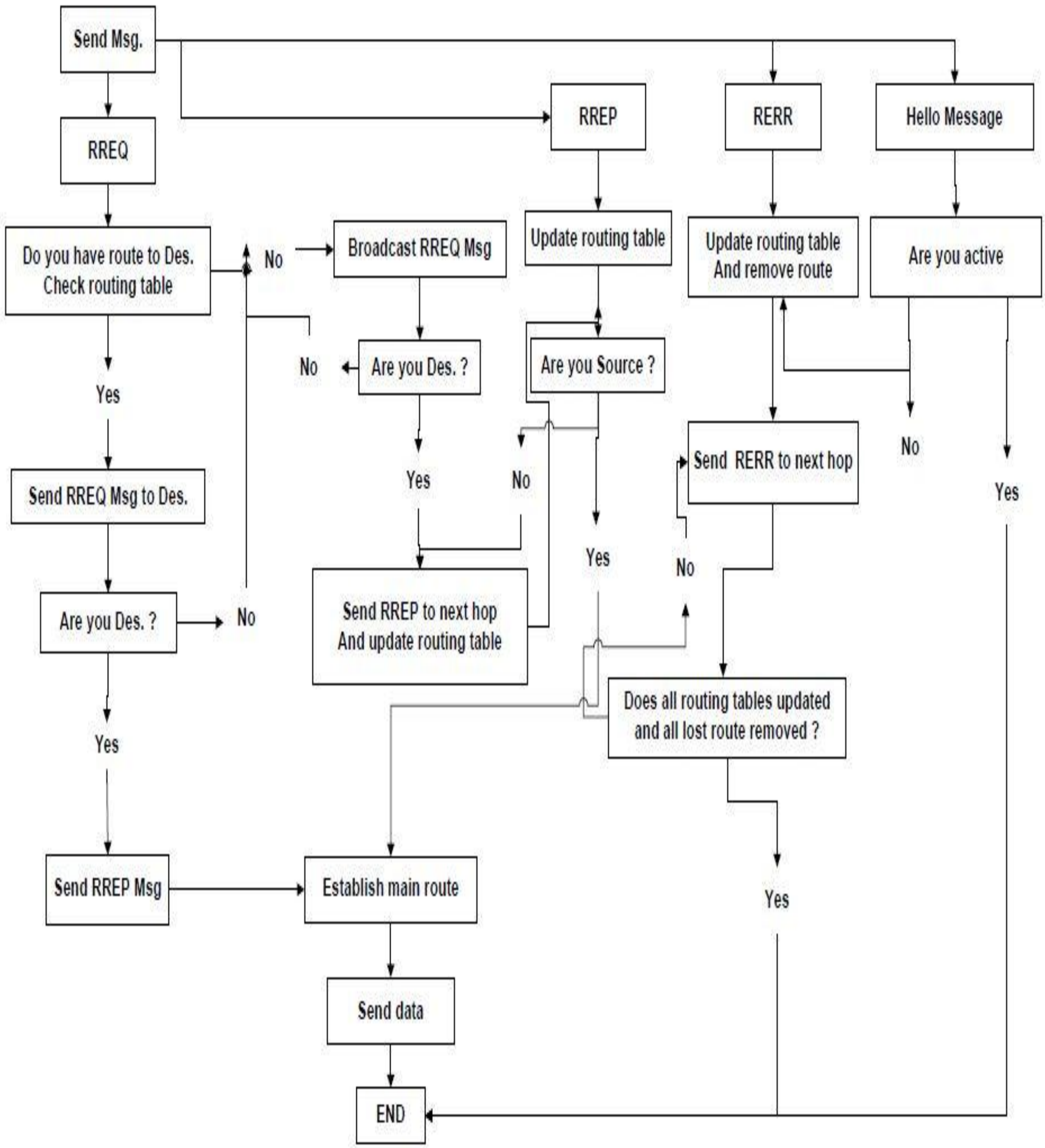

Figure 3.3.4.2 AODV Routing Messages Work Flow.

3.3.4.1 AODV Routing Messages Formats

There are four types of messages AODV is used, Route Request (RREQ) Message, Route Reply (RREP) Message, Hello Message, and Route Error (RERR) Message. The mesh node broadcasts RREQ message to discover a route to the destination node, the routing path will be determined when the message reaches the destination or intermediate node which has a route to the destination node, the destination node will unicast RREP message to the source mesh node, and main route will be established, and data transferring process will be started. Every mesh node will monitor the route status of next hops in only active routes using hello message, if there is link failure in route mesh nodes will use RERR message to notify other nodes in the mesh network by this failure.

3.3.4.2 AODV Routing Table Format

Every mesh node in the mesh network has a routing table to keep routing information. AODV protocol responsible for building a routing table in each node, then it will use routing information in routing table to forward the packets to the destination. When any node in mesh network receive routing request, it will read the message and check the routing table, if there is a routes already there, then it is easy to establish the main route to destination, otherwise the node will update its routing table and broadcast the request again to next hop and so on. AODV deals with route table management using the fields as shown in table (3.1) for routing table structure of AODV.

Destination IP Address
Destination Sequence Number
Valid Destination Sequence Number flag
Other state and routing flags
Network Interface
Hop Count
Next Hop
List of Precursors
Lifetime

Table 3.1 Routing Table Structure of AODV

3.3.4.3 Route Request (RREQ) Message Format

RREQ message is used to look for the route to the destination, and any new connected node will broadcast this message. The following table illustrated the format of the Route Request message which contains the fields as shown in table (3.2):

0 1 2 3

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

<table>
<tr><td>Type</td><td>J</td><td>R</td><td>G</td><td>D</td><td>U</td><td>Reserved</td><td>Hop Count</td></tr>
<tr><td colspan="8">RREQ ID</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Destination Sequence Number</td></tr>
<tr><td colspan="8">Originator IP Address</td></tr>
<tr><td colspan="8">Originator Sequence Number</td></tr>
</table>

Table 3.2 Route Request (RREQ) Message Format of AODV

The table (3.3) explains the contents of the table (3.2) of AODV routing request message.

Field	Usage
Type	1
J	Join flag used for multicast
R	Repair flag used for multicast
G	Gratuitous RREP flag
D	Destination only flag
U	Unknown destination sequence number
Reserved	If 0 ignored on reception
Hop Count	The number of hops from source to destination
RREQ ID	RREQ unique sequence number
Destination IP Address	IP address of the destination
Destination Sequence Number	The latest destination sequence number received in the past
Originator IP Address	The IP address of the source node
Originator Sequence Number	The current sequence number of the source node

Table 3.3: Route Request (RREQ) Message Format of AODV explanation

3.3.4.4 Route Reply (RREP) Message Format

RREP message is produced by the distention node, it is used to notify the source node about availability of the destination node and establish the main route between the source node and the destination node and tell the source node which route it can use to send its traffic. Table (3.4) shows the RREP message fields.

<table>
<tr><td colspan="10">0</td><td colspan="10">1</td><td colspan="10">2</td><td colspan="2">3</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>0</td><td>1</td></tr>
<tr><td colspan="8">Type</td><td>R</td><td>A</td><td colspan="9">Reserved</td><td colspan="5">Prefix Sz</td><td colspan="8">Hop Count</td></tr>
<tr><td colspan="32">Destination IP Address</td></tr>
<tr><td colspan="32">Destination Sequence Number</td></tr>
<tr><td colspan="32">Originator IP Address</td></tr>
<tr><td colspan="32">Lifetime</td></tr>
</table>

Table 3.4: Route Reply (RREP) Message Format of AODV

The table (3.4) illustrated the format of the Route Reply message and the explanation of these fields shows in the table (3.5).

Field	Usage
Type	2
R	Repair flag
A	Acknowledgment
Reserved	If 0 ignored on reception
Prefix Size	Indicates that the next hop will be used for nodes with the same routing prefix
Hop Count	The number of hops from source to destination
Destination IP Address	IP address of the destination
Destination Sequence Number	The destination sequence number associated to the route.
Originator IP Address	The IP address of the source node which originated the RREQ
Lifetime	The time in milliseconds, nodes consider the route of RREP to be valid.

Table 3.5: Route Reply (RREP) Message Format of AODV Explanation

3.3.4.5 Hello Message Format

In AODV routing protocol, active routes between mesh nodes need maintenance process to check the availability of routes and check if there is missing route to insure all active routes are work properly. Hello message is used in AODV routing protocol for this purpose, mesh nodes that are part of active nodes use hello message to periodically offer connectivity information by sending local Hello messages and check the reply, if its neighbor node replied this mean the active route is work properly. Otherwise, the neighbor is currently lost, and there is a failure in this route. Hello message has RREP message fields with the following changes:

Hop count = 0

Lifetime = ALLOWED_HELLO_LOSS * HELLO_INTERVAL

3.3.4.6 Route Error (RERR) Message Format

AODV will maintenance the active routes using hello message, and when one route is lost, other nodes should notify its neighbors about lost route and update their routing table to remove lost route. RERR message is used for this purpose and used fields same as shown in the table (3.6).

0 1 2 3

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

Type	N	Reserved	Dest Count
Unreachable Destination IP Address			
Unreachable Destination Sequence Number			
Additional Unreachable Destination IP Addresses (if needed)			
Additional Unreachable Destination Sequence Numbers (if needed)			

Table 3.6: Route Error (RERR) Message Format of AODV

The table (3.6) illustrated the format of the Route Error message which contains the following explanation of the fields as shown in table (3.7).

Field	Usage
Type	3
N	No deleted flag
Reserved	If 0 ignored on reception
DestCount	The number of unreachable destinations nodes
Unreachable Destination IP Address	Unreachable IP address of the destinations nodes
Unreachable Destination Sequence Number	The sequence number of unreachable IP address of the destinations nodes

Table 3.7: Route Error (RERR) Message Format of AODV Explanation

Chapter4

Routing Metrics

4.1 Routing Metrics and Routing Performance Evaluation in WMN

WMN is multi-hop network, and the source node has multiple routes to the destination node. Making routing decisions is the core function of the router. Router function becomes more difficult when there are many routes to the same destination. Routing metrics are used to help the router to make correct routing selection and decisions to select the optimal routing path from the source node to the destination node with minimum routing cost and high performance. Every route has routing metrics that are calculated and assigned in the routing table through routing protocol. Routing protocols (proactive or reactive routing protocols) help the mesh routers to calculate routing metrics and exchange and propagate the routing information including routing metrics between all available nodes, these metrics help mesh routers in the WMN to have full information about all routes and which route is better than another route regarding routing metrics.[20]

4.2 Routing Metrics Optimization Objectives

The routing protocols and routing algorithms use routing metrics to achieve many of the objectives such as:

- Delay: routing metrics used to minimize delay, and routing path with minimum delay will be selected to deliver data from the source node to the destination node, but we have to take some metrics in account such as bandwidth, interference, hop-count, route reliability etc.
- Probability of data traffic delivery: The main goal of routing optimization is to deliver data traffic with minimum losing data ratio, sometimes we are pushed to maximize the delay but ensure the probability of data traffic delivery.
- Maximize Network routes throughput: Selecting high capacity, and big bandwidth will increase the throughput and network performance.
- Load Balancing: Because WMN is multi-hop network, and there are multiple routes can be used to distribute the load between available routes which will cause to increase the reliability, throughput, and performance of the network and ensure the fault tolerance.

4.3 Routing Metrics Computation

Routing metrics computation process is very important, because during the running time of wireless network the environment and the load in mesh routers are always changing, the routes metrics which have been stored in the routing table must regularly be updated, any change or update in routing metrics in one router should be propagated to all routers, this will insure correct routing decisions. Metric updates propagation will consume the bandwidth and increase the load in wireless links so this routing metrics computation and updating need to be controlled and organized through routing protocols algorithms. Bandwidth measurements can be done through observing the incoming traffic and outgoing traffic in mesh nodes, other packets are generated by routing protocols to calculate the routing metrics, the optimization process still in progress in this field, and researchers are looking for optimal routing metrics to insure that router will make the correct decision in optimal route selection.

4.4 Routing Metrics

There are many routing metrics designed for WMN to optimize the mesh network performance because the limit of bandwidth in WMN and the environment around the mesh network also always change.

4.4.1 Hop Count

Routing protocols such as OLSR, DSR, DSDV and AODV in WMN use hop count as default metric and select shortest path with minimum hop count from the source node to the destination node. Hop count is the simplest routing cost metric which mean the total number of intermediate mesh nodes along the routing path same as shown in Figure (4.4.1). The routing optimization process aims to minimize hop count by selecting the shortest route. Fewer hop counts in the routing path imply smaller delay, high throughput and reduce the number of data dropping. Shortest route has some disadvantages because it will have high congestion because a lot of mesh nodes will use the shortest route to forward the traffic, and the congestion will decrease the throughput and performance of the mesh network.

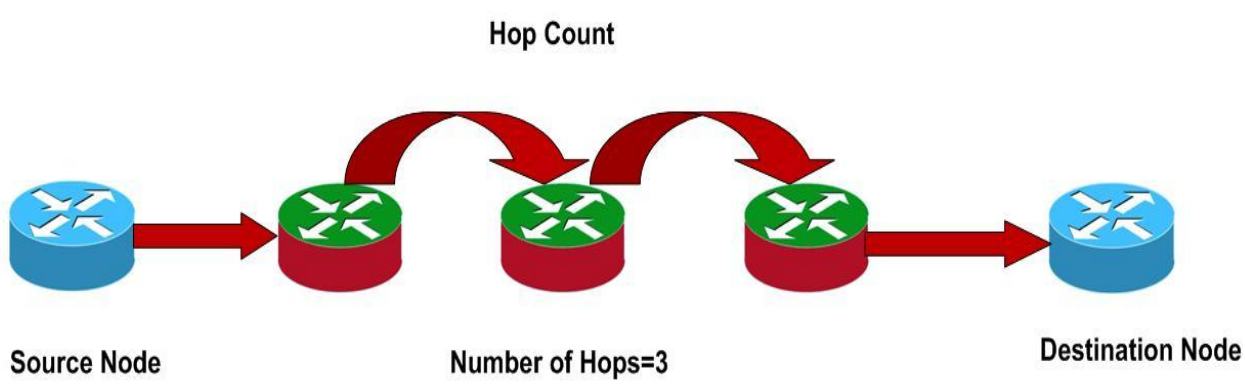

Figure 4.4.1 Hop Count

4.4.2 Signal Strength Metrics

Signal strength is very important to establish a wireless connection between mesh routers in WMN, and signal strength should exceed the threshold value in wireless interfaces to ensure the connection. The link quality depends on signal strength, and high signal strength will make high-quality wireless link and big distance between mesh nodes needs signal with enough power to establish a wireless connection. The sender router and the receiver router will never be able to establish a connection and exchange data if one of them doesn't exceed required signal strength threshold value. Routing protocols algorithms will avoid using routing paths with very weak signal because this route is not stable, and routers can't trust it.

4.4.3 Per-Hop Round Trip Time (RTT)

RTT used to measure the average delay in wireless links between mesh routers. Mesh router sends periodically probe packets every 500ms to each neighboring mesh routers and each neighbor mesh router will respond immediately with probe packets acknowledgement with a time-stamp, the sender mesh node uses the probe packets acknowledgement to compute the RTT value and keep it. RTT is affected by queue length, link quality, bandwidth congestion and ect. Routing protocols use RTT information to select the routing path with the least sum of RTT. RTT is simple routing metrics, and it is good to calculate delay between mesh routers, but there are some disadvantages such overhead of sending and receiving RTT packets and produce self-interference.[24]

4.4.4 Per-hop Packet Pair Delay (PktPair)

In PktPair routing metric, the mesh router periodically sends two back-to-back packets to each neighbor, and first packet is small (137 bytes) and the other is large (1000 bytes), neighbor mesh routers calculate the delay time between arrival two packets and report back to the sender to be used as the cost metric for the link. [24]

4.4.5 Expected Transmission Count (ETX)

Expected transmission count (ETX) is one of the routing metrics uses to measure the wireless link quality and the packet loss rate between mesh nodes. ETX are used to calculate the expected number of transmissions and retransmissions is required to send a packet over a wireless link because minimizing the number of transmissions and retransmissions will optimize the mesh network performance and maximize network throughput, and minimize mesh network bandwidth consuming. ETX is calculated by the following equation:

$$ETX = \frac{1}{\mathrm{Df} * \mathrm{Dr}} \tag{4.1}$$

In the equation (4.1) (df) is the forward delivery ratio and (dr) is the reverse delivery ratio The ETX of a routing path is defined as the sum of ETX of individual wireless links composing the routing path, high ETX mean this route is low quality and will consume the mesh network resources. The ETX estimating process is done periodically by exchanging probe packets among mesh nodes. [20],[24]

4.4.6 Expected Transmission Time (ETT)

ETX is used to measure the packet loss rate in the routing path but not its bandwidth, and calculate the expected number of transmissions and retransmissions are required to send a packet over a wireless link in the mesh network. Expected Transmission Time (ETT) is proposed to optimize the performance of ETX metric in multi-radio WMNs that support different data rates so ETT able to identify high-throughput routes by computation the bandwidth of mesh network links. ETT is calculated by the following equation:

$$ETT = \mathrm{ETX} * \frac{\mathrm{S}}{\mathrm{B}} \tag{4.2}$$

Where S in the equation (4.2) is the size of the packet and B is bandwidth of the link, to measure the bandwidth of mesh network link. The mesh router sends two probe packets with different sizes, small packet is (137 bytes) and large packet is (1137 bytes) to each of its mesh neighbors every minute. Each mesh neighbor measures the arrival time between the small packet and large packet and send back to the sender of probe packets a report. The sender can estimate the bandwidth capacity of the link through the probe packet. The bandwidth is estimated by the sender router by dividing the larger packet size by the smallest delay sample. [20]

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4.4.7 Weighted Cumulative ETT (WCETT)

Weighted Cumulative ETT (WCETT) is an extension over ETX and ETT because ETX and ETT do not care about the intra-flow interference in the routing paths in the mesh network. WCETT was proposed to reduce the number of mesh routers that transmit on same wireless signal channel in routing path.

4.4.8 Metric of Interference and Channel Switching (MIC)

MIC optimizes WCETT by considering in problem of intra-flow and inter-flow interference. Intra-flow interference is the interference among intermediate mesh routers sharing the same routing path but inter-flow interference is the interference among neighboring mesh routers using the same channel. MIC is calculated by the following equation:

$$MIC(p) = \frac{1}{N \times \min(ETT)} \sum_{link\, l \in p} IRU_l + \sum_{node\, i \in p} CSC_i \tag{4.4}$$

Where N in the equation (4.4) is the number of mesh routers in the mesh network, and min(ETT) is the minimum ETT in the mesh network, and IRU (Interference-aware Resource Usage) and CSC (Channel Switching Cost) are computed by the following equation:

$$\begin{aligned} IRU_l &= ETT_l \times N_l \\ CSC_i &= \begin{cases} w_1 & if\ CH(prev(i)) \neq CH(i) \\ w_2 & if\ CH(prev(i)) = CH(i) \end{cases} \quad 0 \le w_1 \le w_2 \end{aligned} \tag{4.5}$$

Where Nj in the equation (4.5) is set of neighbors mesh routers that use link j in data transmission with channel (j) and prev(j) is the previous hop of mesh router j along the routing path.

MIC metric optimizes the mesh network performance because it considers intra-flow interference and inter-flow interference, but the disadvantage of MIC is overhead of estimate the routing path MIC value when the mesh network very big. [20]

4.4.9 Traffic Load Routing Metric

Traffic load on mesh routers is captured by using The buffer utilization (Butz) , Butz is a buffer in mesh routers that contains outbound packets, these packets are ready to be transmitted by physical layer in the mesh router, and the size of Butz is computed as the number of remaining packets in the buffer. Traffic load is computed by the following equation:

$$\mathrm{Load} - \mathrm{count} = \sum_{i=1}^{n} \mathrm{Loadi} \tag{4.6}$$

Where ($load_i$)is the traffic load in mesh router i. Avoiding loaded mesh routers will optimize the mesh network throughput and performance, and using loaded mesh routers will defer the delivery or will drop the packets.

Routing metrics are used to measure the wireless routes quality. Every routing protocol uses special metric to select between available routes. Most of multi hop routing protocol use hop count as a routing metric. In this thesis we add two more metric with hop count to make the router select the optimal route and distribute the traffic between available routes. Signal strength and buffer utilization are used with hop count as a routing metrics to make routing decisions.

Chapter5

Results and Analysis

5.1 WMN Performance Evaluation

This chapter will deal with the evaluation of the optimization of WMN performance and routing protocol behavior on the mesh network on the basis of graphs obtain during simulation in OPNET Modeler 14.5. We focus in my optimization by using load balancing (LB) and evaluate the performance of the mesh network regarding the load balancing technique between mesh routers and gateways. The graphs will be critically evaluated, and reasons will be discussed for each graph behavior. There are some metrics will be used to evaluate the optimization of WMN performance and routing protocol behavior on the mesh network, and later part of the chapter deal with the performance of the network for this thesis.

5.2 Scenarios Detail

There are total twelve different scenarios that have been simulated in this research. The figure (5.2.1) shows the names of scenarios in this thesis.

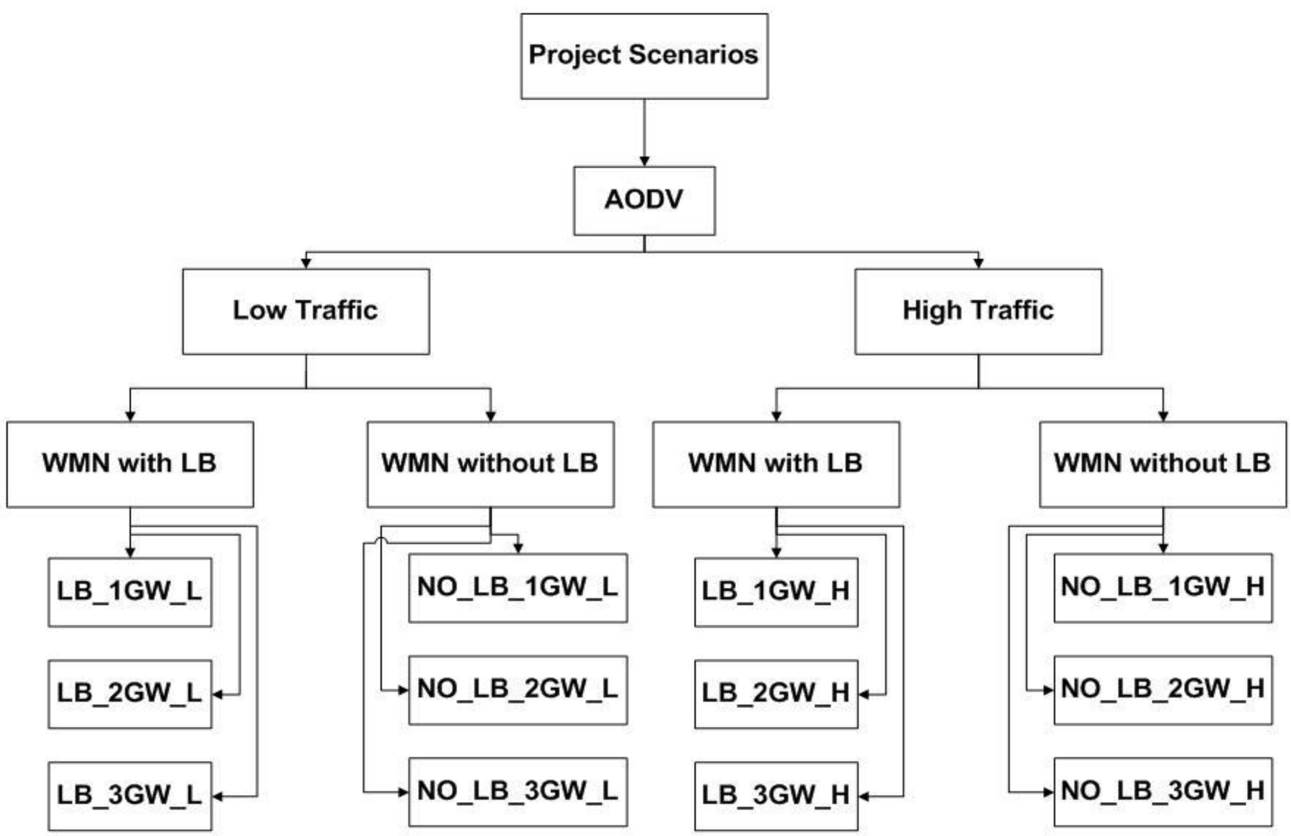


Figure 5.2.1 Project scenarios

All scenarios in figure (5.2.1) were set up and configured in OPNET Modeler 14.5, and the scenarios are working properly without errors using AODV as a routing protocol. AODV is also required to configure on the end node because it's a reactive routing protocol, and if end nodes don't have AODV configured, the nodes will be unable to send routing request for the routing path and no communication will be possible. There are total twelve scenarios that will be discussed in this section. The topology for all scenarios will be different but same in generation of traffic.

5.3 Symmetric WMN and Asymmetric WMN

The figures (5.3.1-5.3.4) for the cases WMN with load balancing (LB) and cases of WMN without load balancing (NO_LB) in AODV.

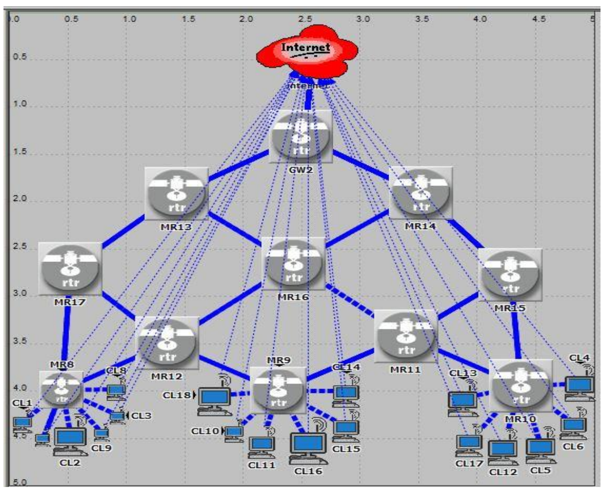


Figure 5.3.1 LB_1GW Scenario

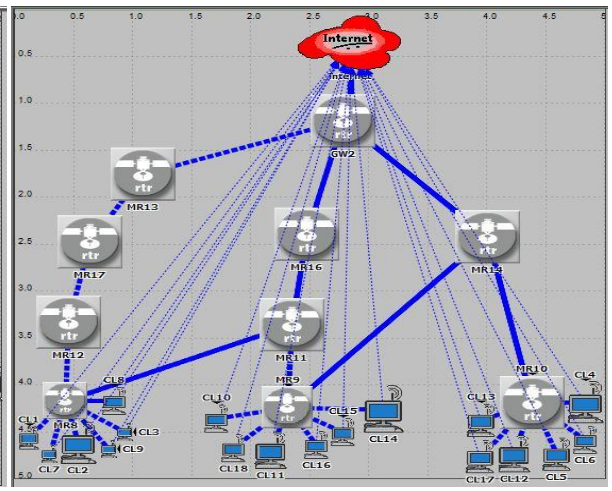


Figure 5.3.2 NO_ LB_1GW Scenario

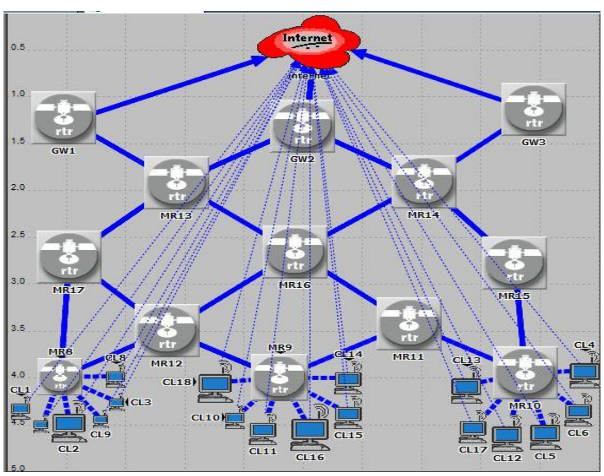


Figure 5.3.3 LB_3GW Scenario

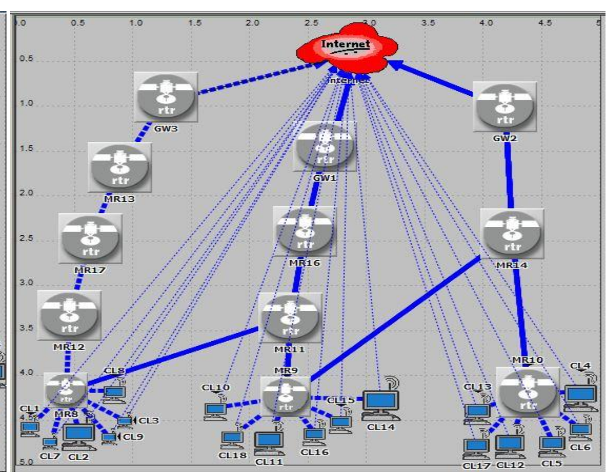
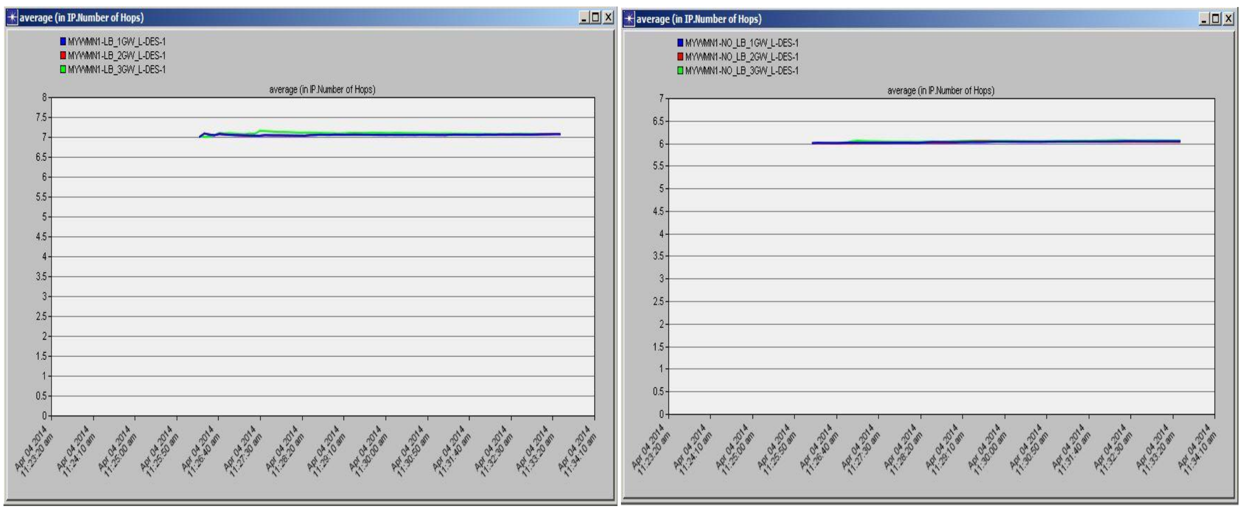


Figure 5.3.4 NO_ LB_3GW Scenario

It can be observed from the figures (5.3.1-5.3.4) that with load balancing the load is distributed across all the mesh routers and gateways in balancing mode while in case of without load balancing some of the mesh routers and gateways are used more than others because AODV select the shortest path to destination, the effect of this scenario will be analyzed from graphs. The remaining scenarios are also the same topology except with the number of gateways in the mesh network, therefore, snap shot for two gateways scenarios were not provided because it is same topology but with difference in number of gateways.

5.4 AODV Performance

OPNET generates different statistics for the performance metrics of AODV protocol. The important statistics to observe the difference in scenarios is shown in the figures below.



a) LB Scenarios

b) NO_LB Scenarios

Figure 5.4.1 Number of Hops per Route in LB and NO_LB Scenarios

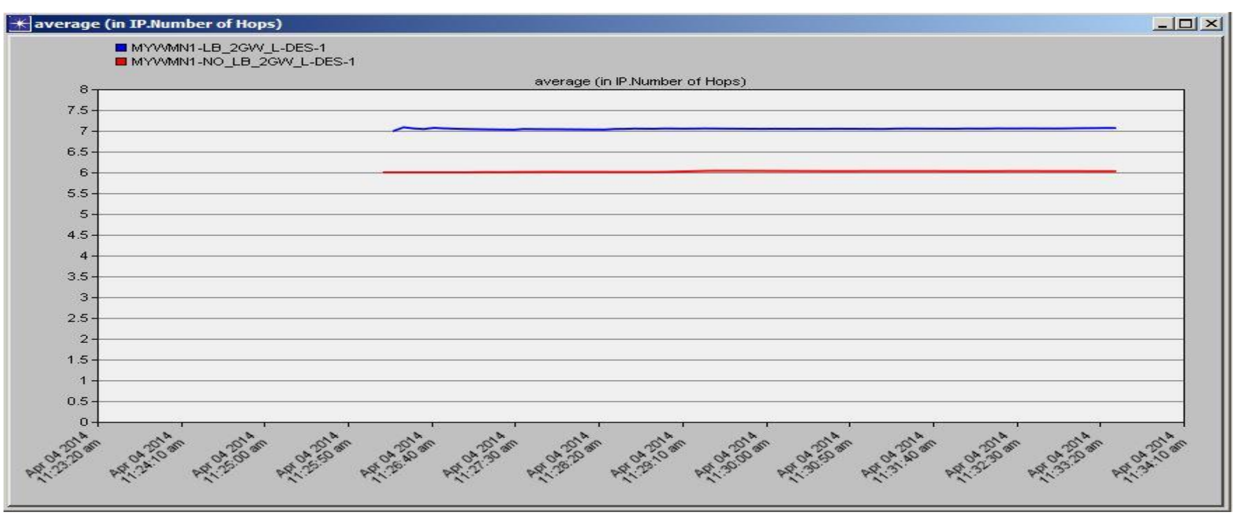
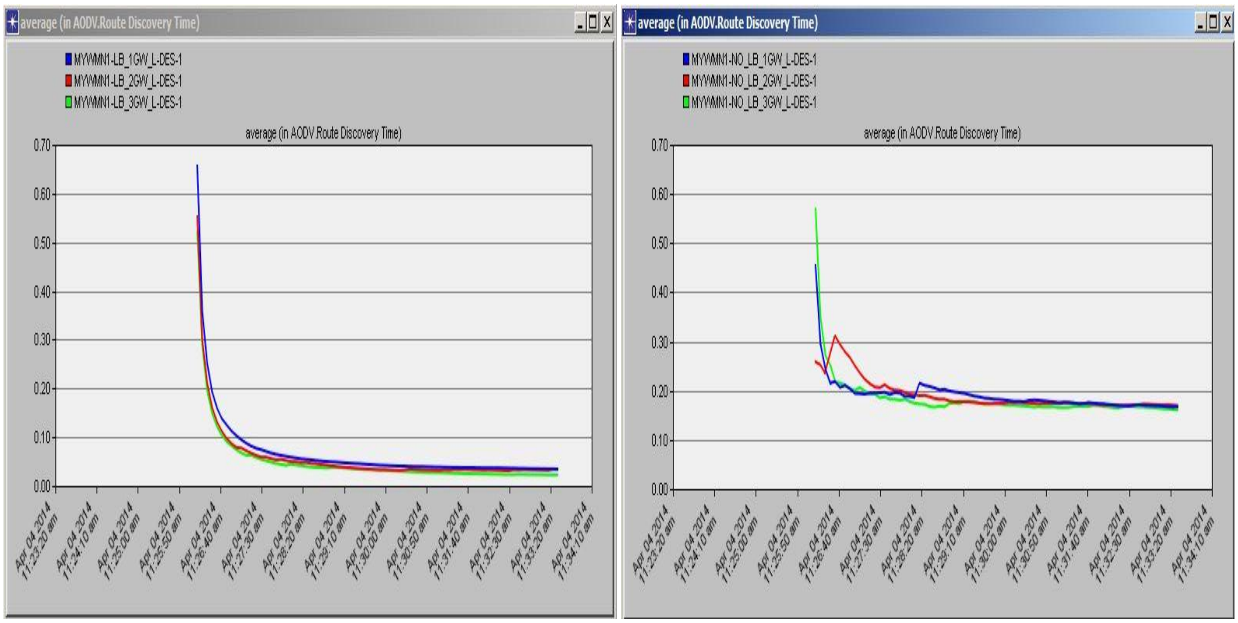


Figure 5.4.2 Number of Hops per Route in LB_2GW Scenario and NO_LB_2GW Scenario



a) LB Scenarios b) NO_LB Scenarios

Figure 5.4.3 Route Discovery Time in Low Traffic Scenarios

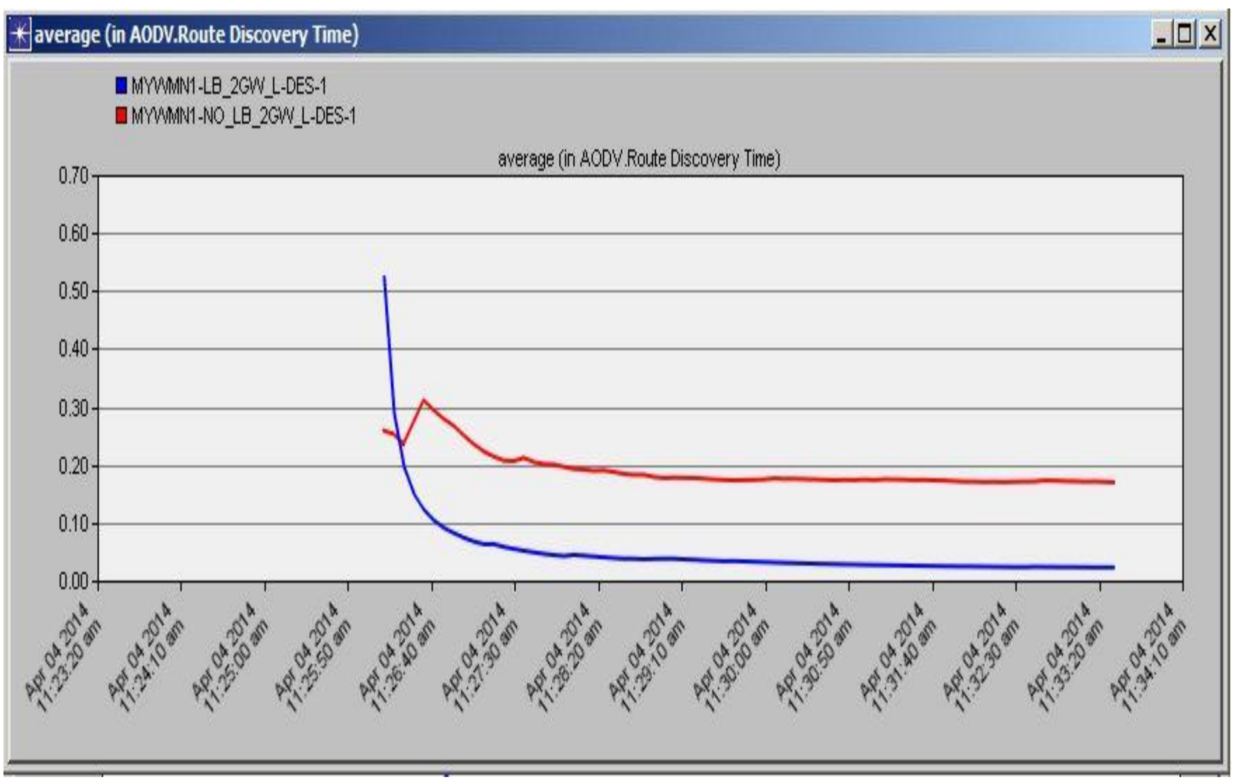
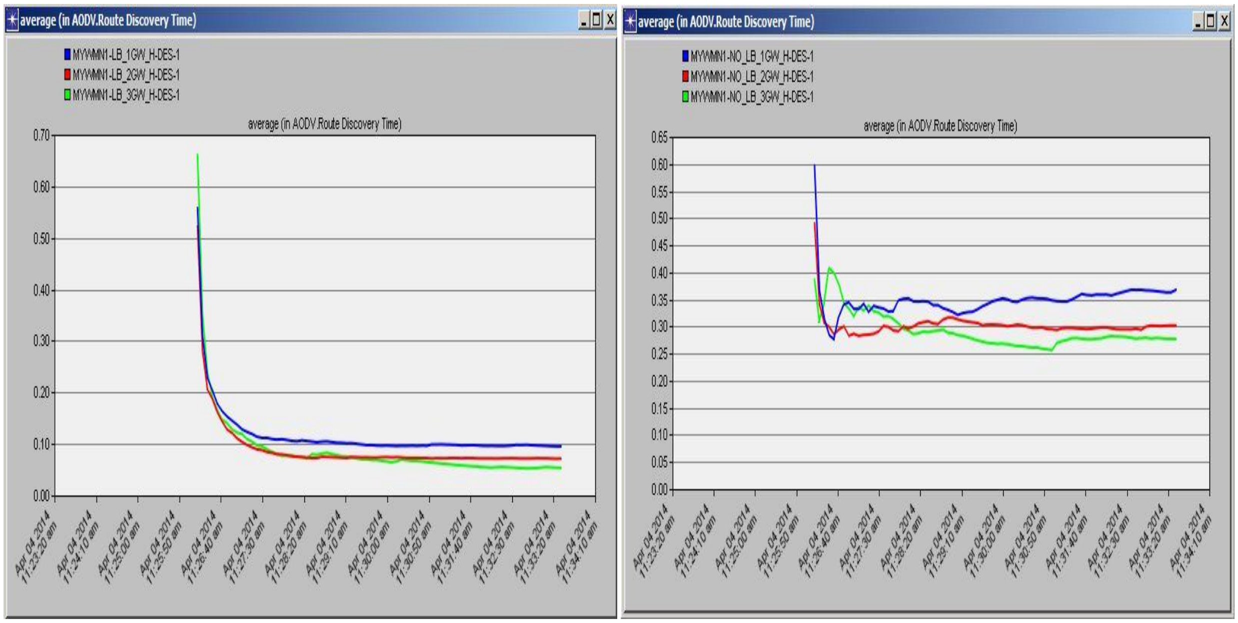


Figure 5.4.4 Route Discovery Time in Low Traffic LB_2GW Scenario and NO_LB_2GW



a) LB Scenarios b) NO_LB Scenarios

Figure 5.4.5 Route Discovery Time in High Traffic Scenarios

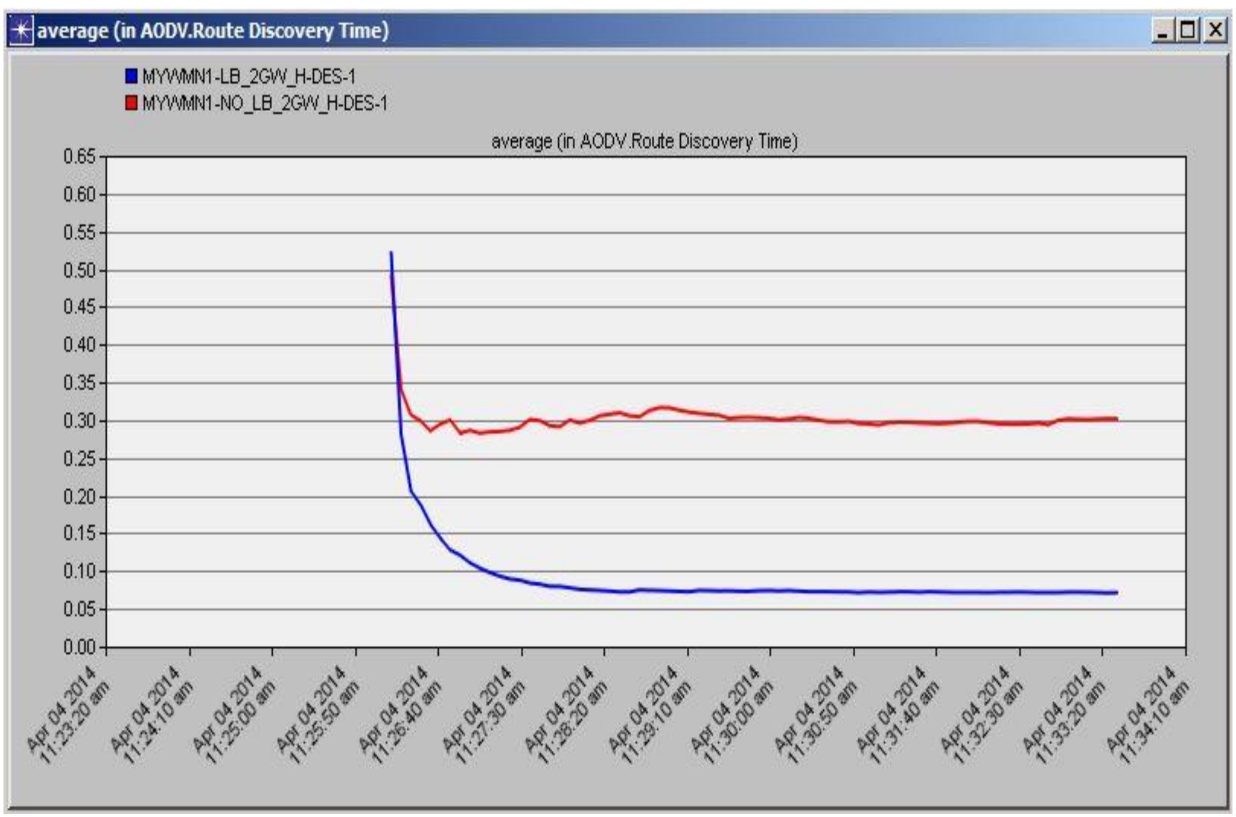
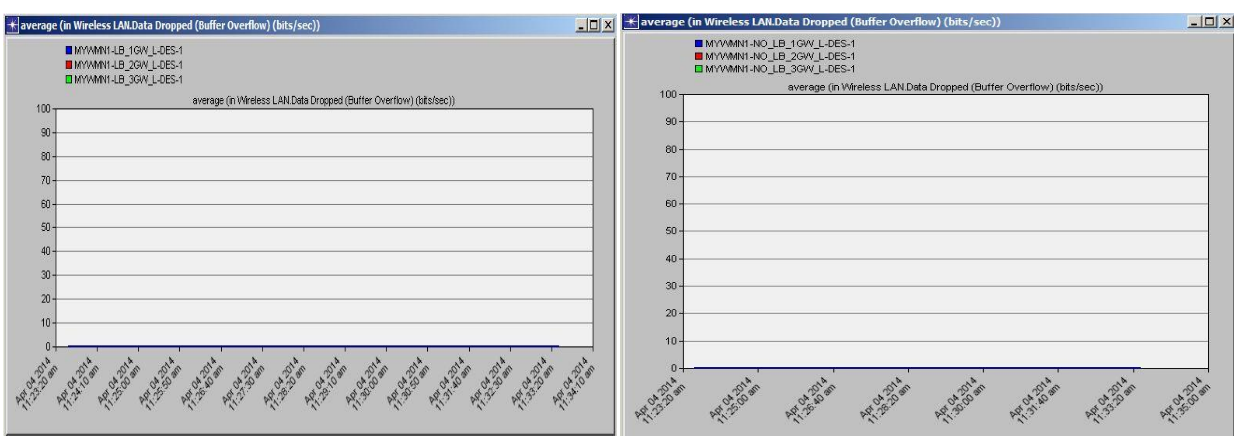


Figure 5.4.6 Route Discovery Time in High Traffic LB_2GW Scenario and NO_LB_2GW

OPNET draws various graphs for AODV statistics, but these two statistics are related to this thesis to discuss the scenario performance effect on AODV. As discussed above AODV is a reactive routing protocol, whenever the client have some data to send, and the previous un active path was removed it will broadcast a routing request for new routes. Figure (5.4.1) shows us that the number of hops in every scenario is different. In LB scenarios there are seven hops, four hops are the mesh routers, the fifth is the gateway, the sixth is the ISP router and the seventh is the ISP router that destination host connected to it, the number of hops in route will be increased if we add more hops in mesh network. In No_LB scenarios, the number of hops is six less than LB scenarios by one, this is the average of the number of hops in all routes, if we focus in figure (5.3.1) there are three main routes the number of hops in the first route is five, the second route is six, and the third route is seven then the average for all is six hops per route. Route discovery in figures (5.4.3-5.4.6) is the time in which client broadcast request for the path and get replied from the distention. Routing discovery time takes a lot of time at the beginning of running the simulation. WMN in the first start up doesn't have any routes, so all the nodes will broadcast many requests to find out route to the destination. In LB scenarios, the route discovery time is less than other scenarios, because the cost of all routes are equal so all the routing requests will be distributed in balancing between available routes. Maximum route discovery time was shown in NO_LB scenarios. The congestion and overloading in some nodes in shortest route will increase the waiting time of RREQ packets in buffer queue that is why the discovery time in NO_LB scenarios is the maximum, the opposite happen in LB scenarios.

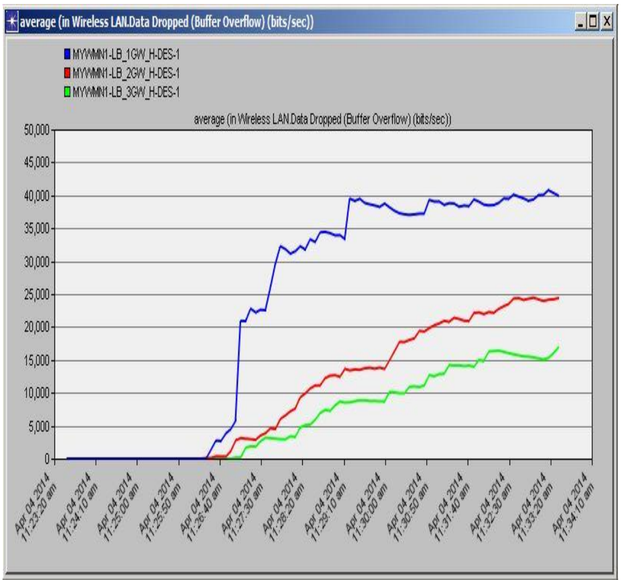
5.5 Wireless Network Performance

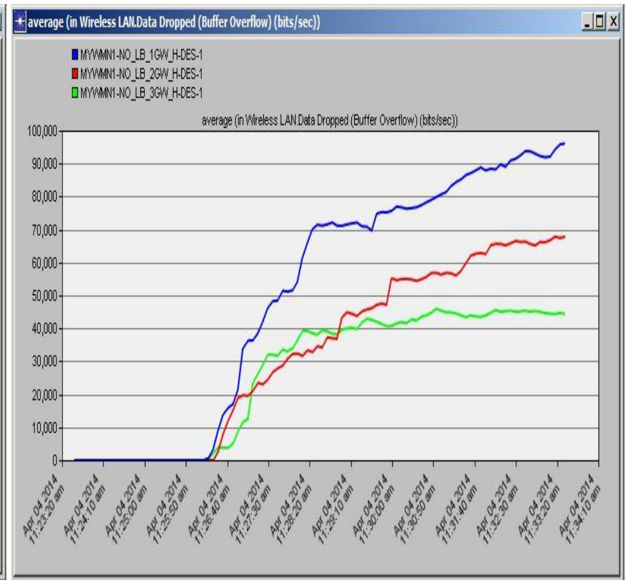
The main focus of the network design and implementation is to optimize the WMN performance metrics. On the basis of performance metrics that we will discuss in this chapter, various results have been generated for different scenarios using OPNET. The results are shown in graphs from OPNET modeler 14.5



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.1 Data Dropped in Low Traffic Scenarios





a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.2 Data Dropping in High Traffic Scenarios

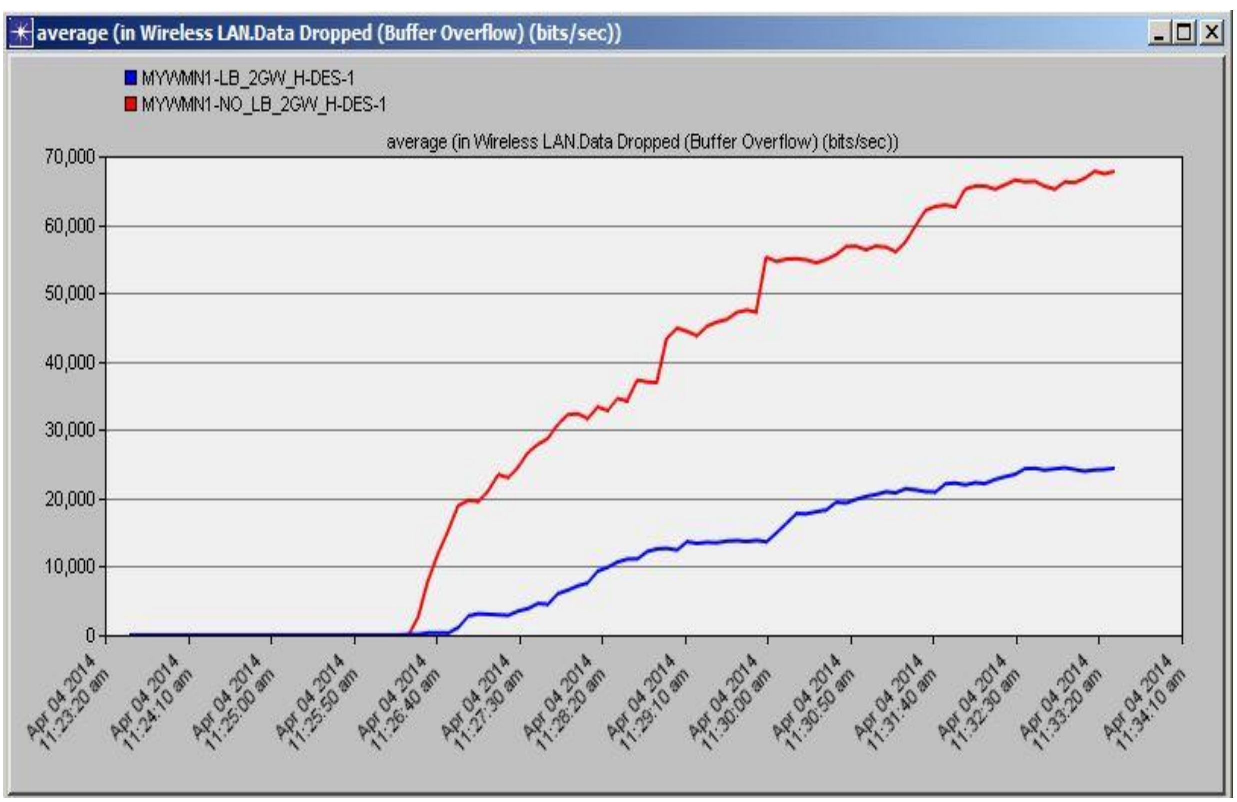
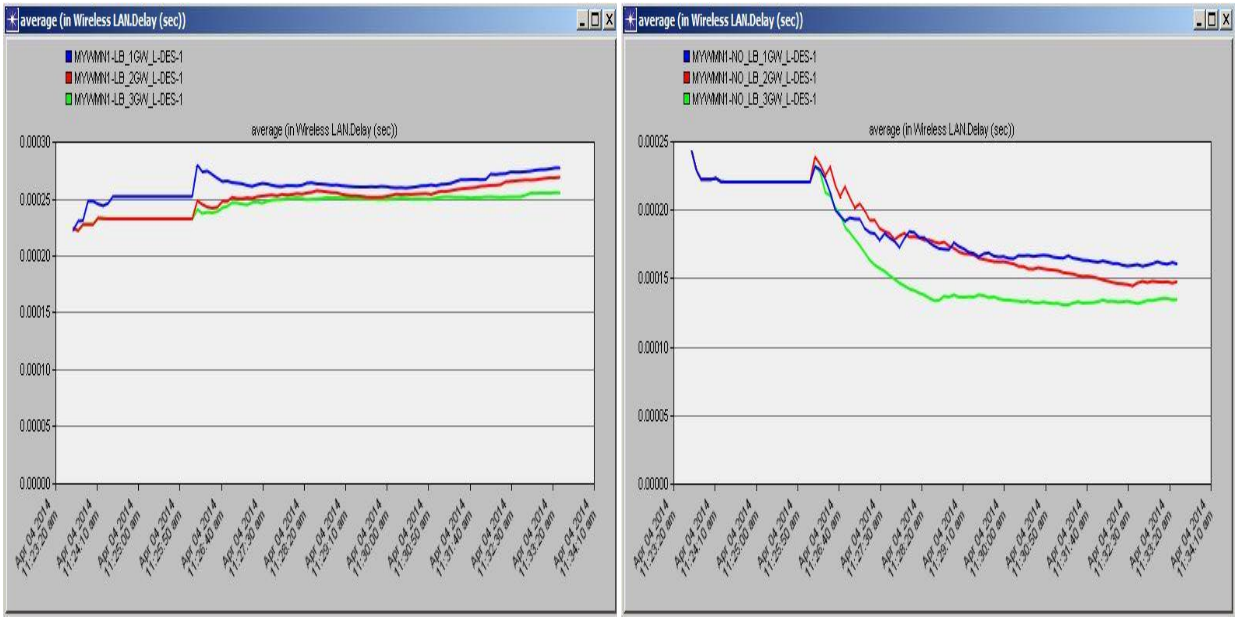


Figure 5.5.3 Data Dropped in High Traffic LB_2GW Scenario and NO_LB_2GW Scenario



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.4 Delay in Low Traffic Scenarios

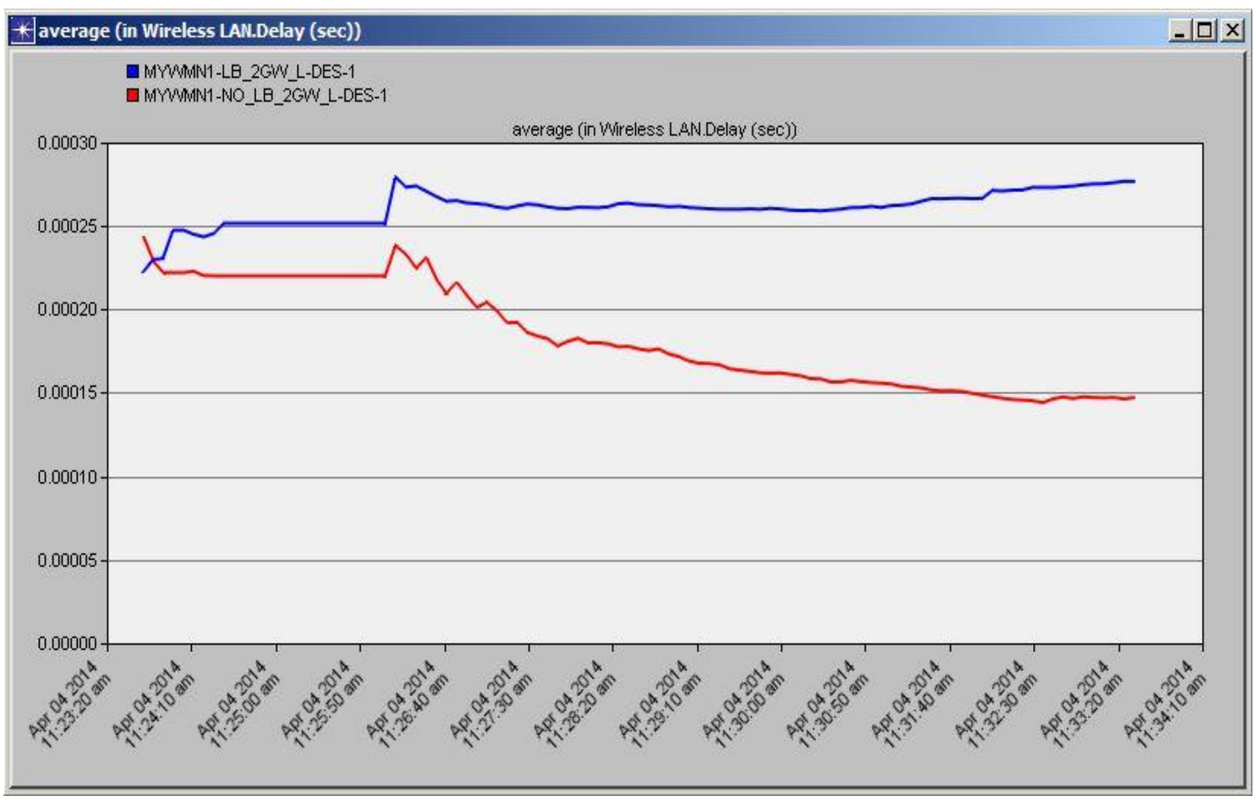
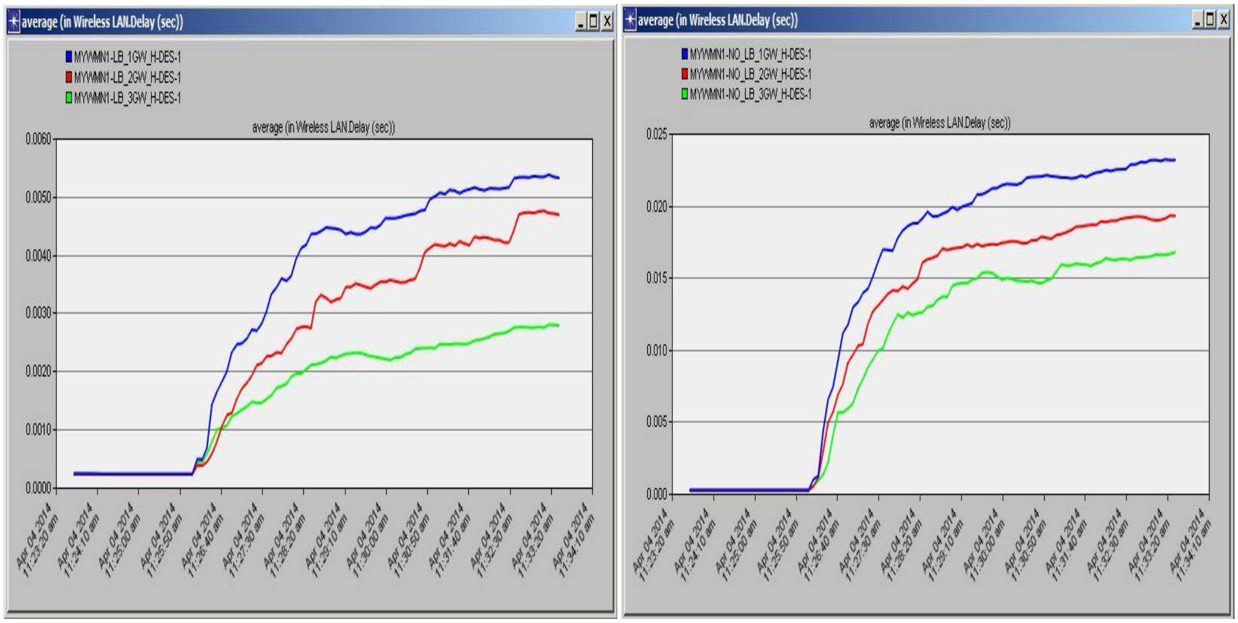


Figure 5.5.5 Delay in Low Traffic LB_2GW Scenario and NO_LB_2GW Scenario Scenarios



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.6 Delay in High Traffic Scenarios

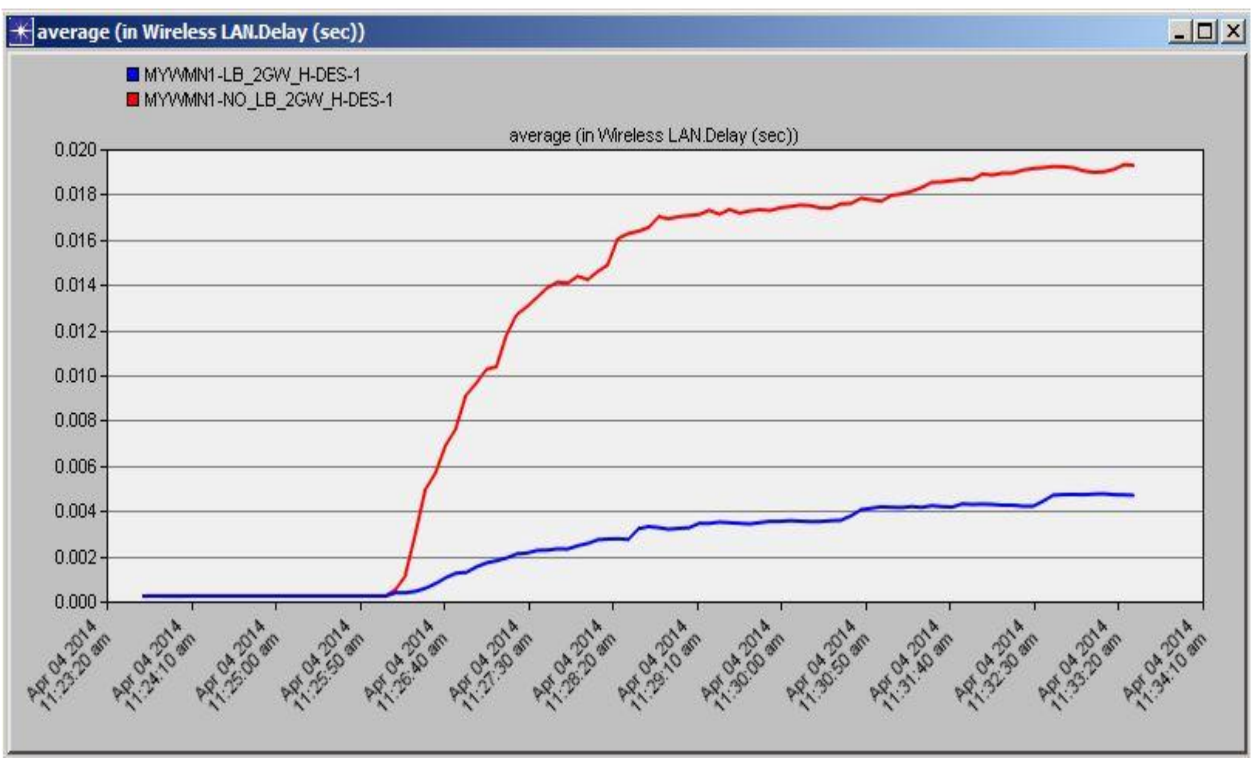
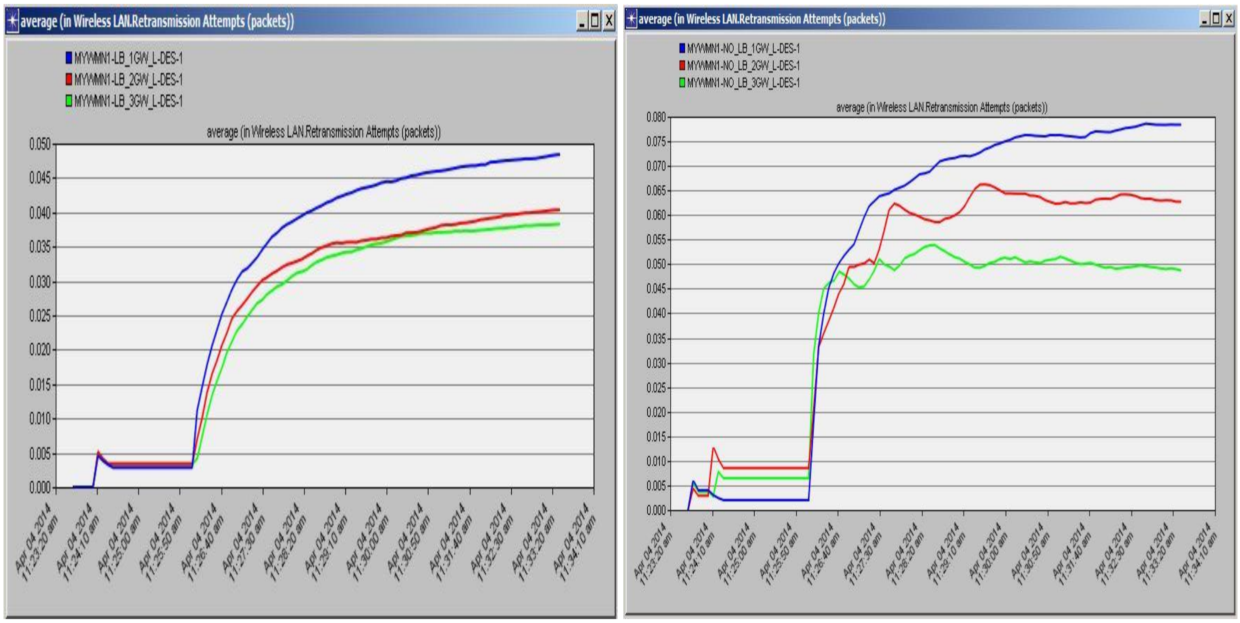


Figure 5.5.7 Delay in High Traffic LB_2GW Scenario and NO_LB_2GW Scenario Scenarios



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.8 Retransmission Attempts in Low Traffic Scenarios

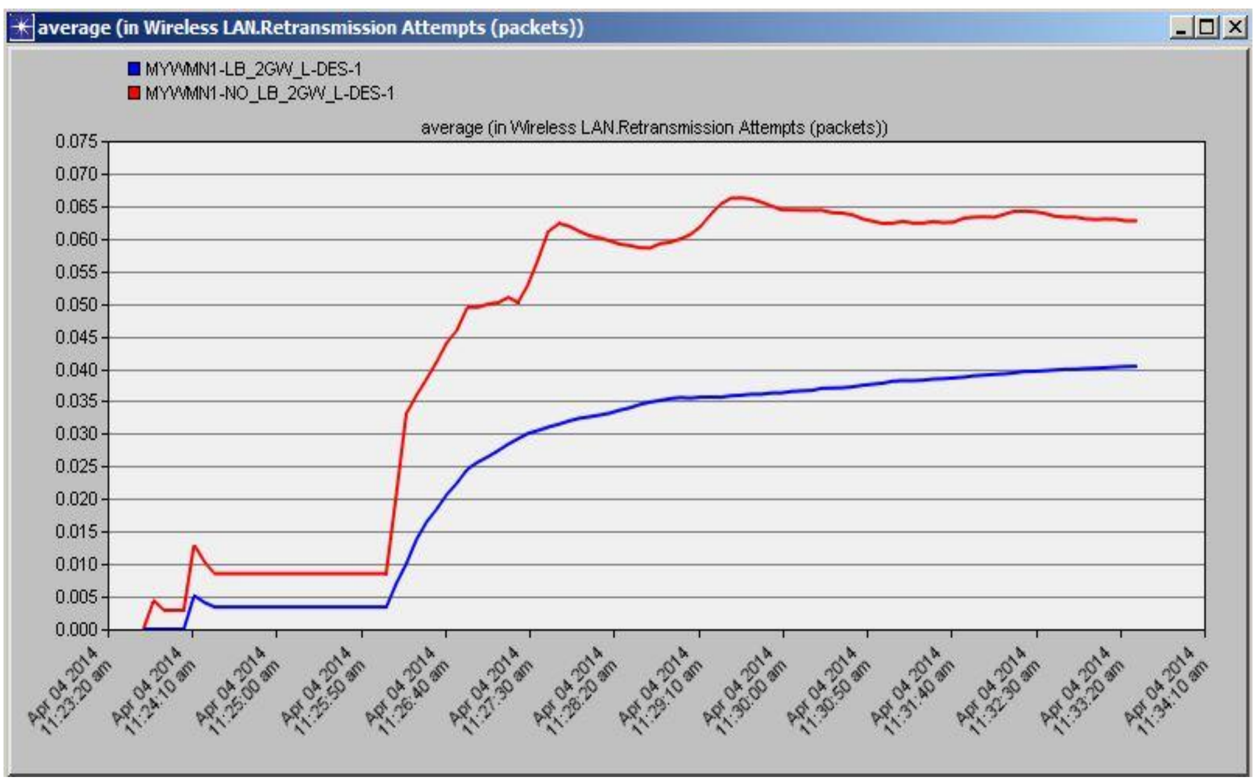
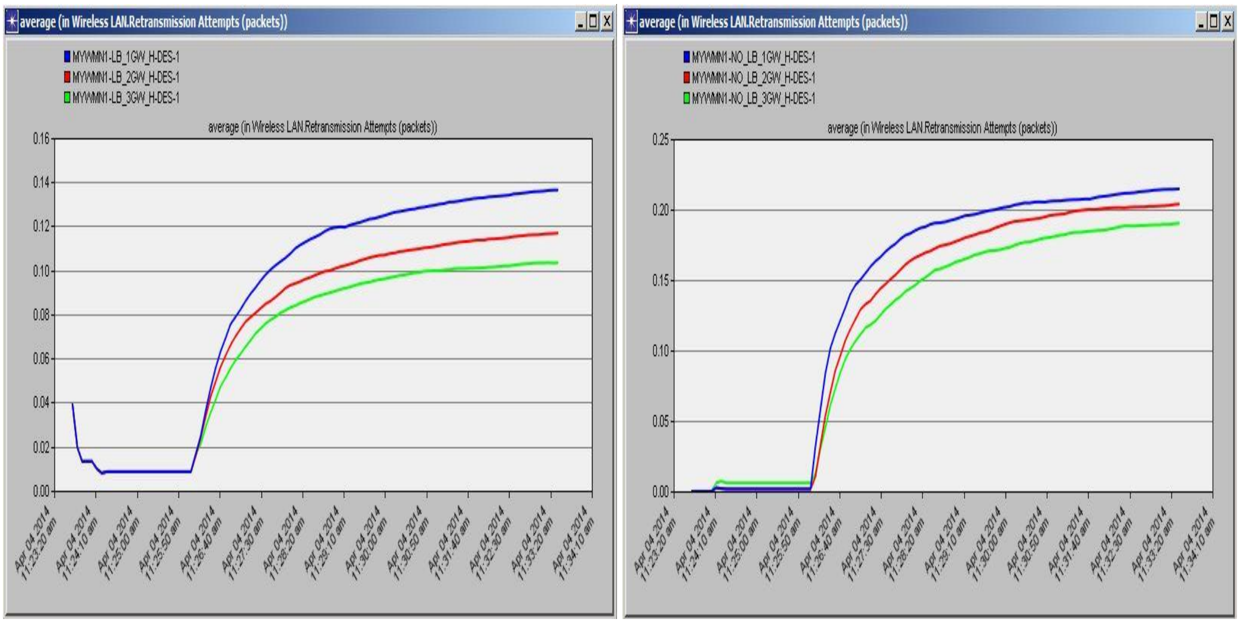


Figure 5.5.9 Retransmission Attempts in Low Traffic LB_2GW Scenario and NO_LB_2GW Scenario



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.10 Retransmission Attempts in High Traffic Scenarios

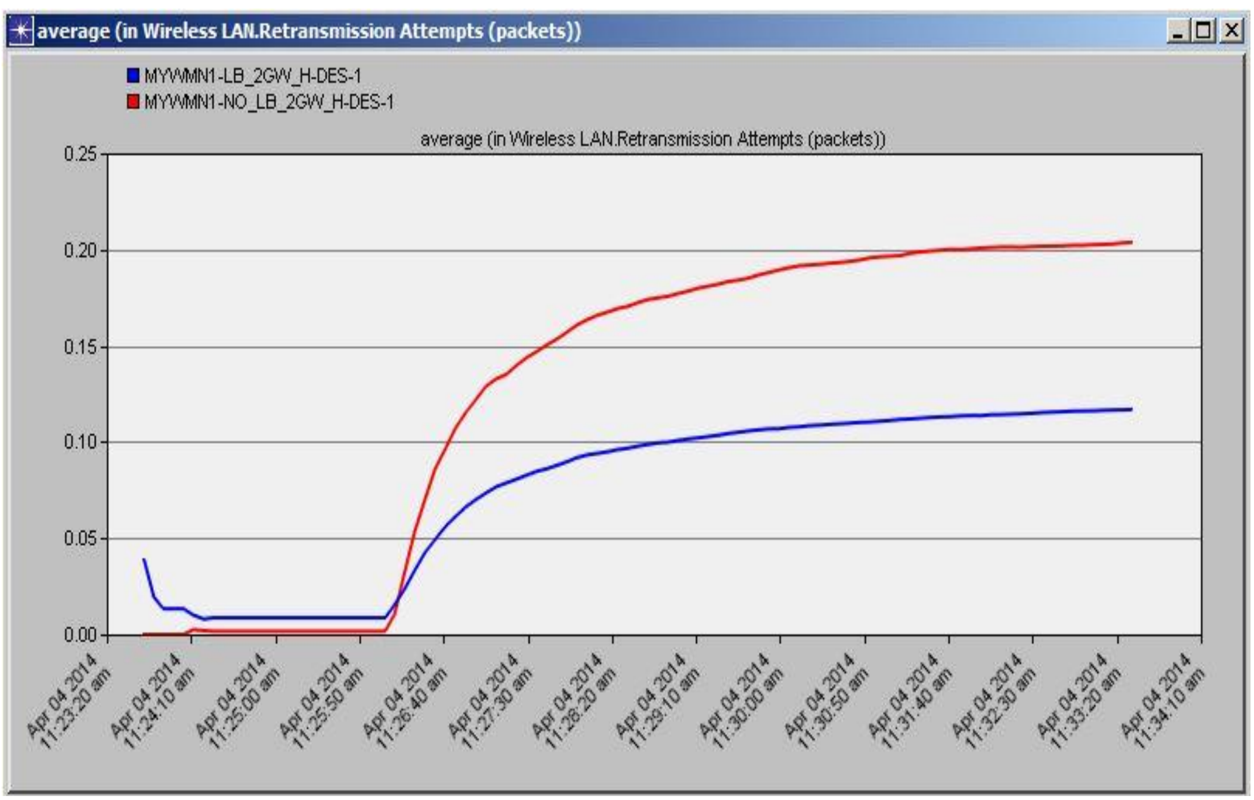
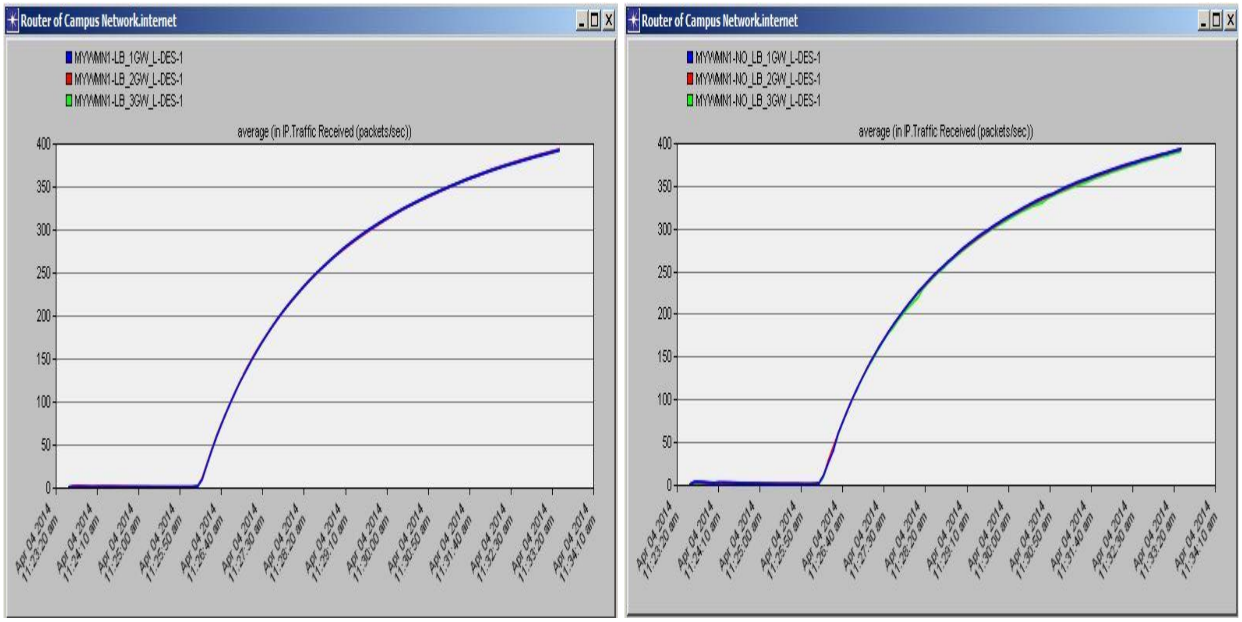


Figure 5.5.11 Retransmission Attempts in High Traffic LB_2GW Scenario and NO_LB_2GW



a) LB Scenarios   b) NO_LB Scenarios

Figure 5.5.12 Throughput in Low Traffic Scenarios

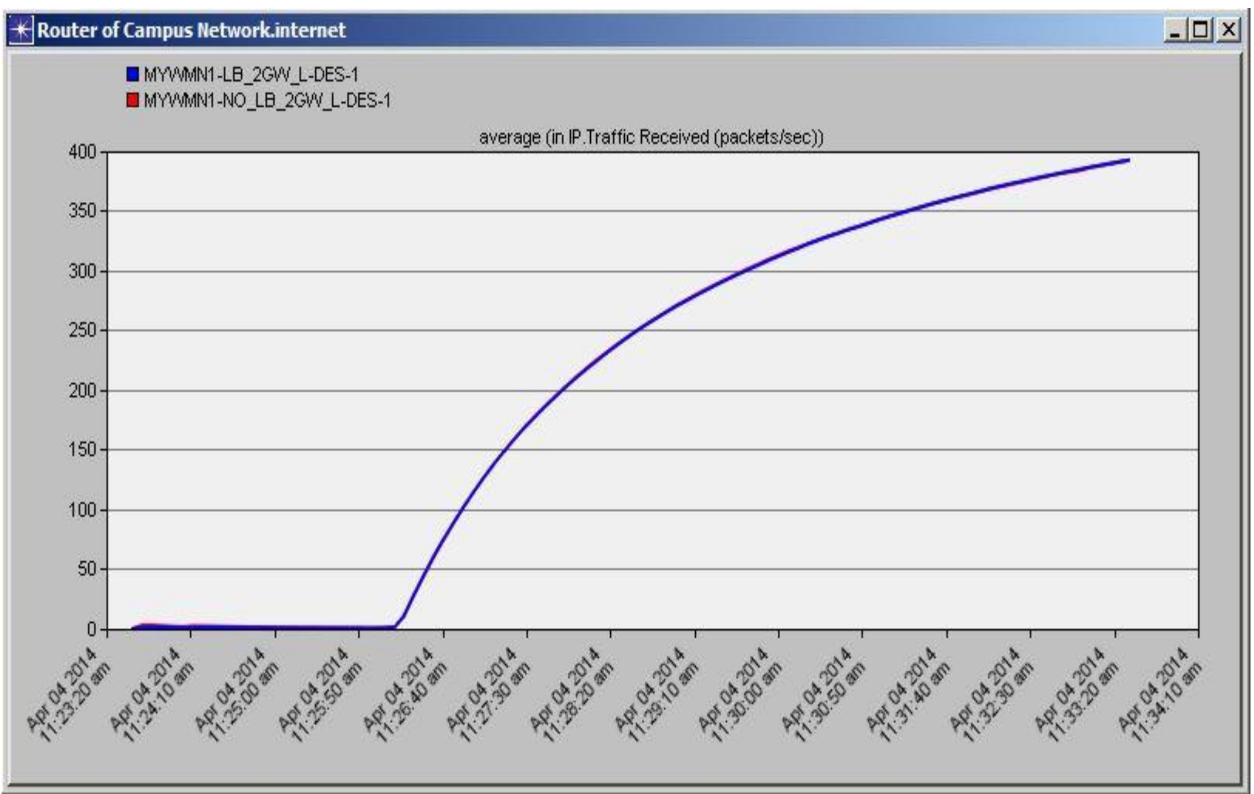
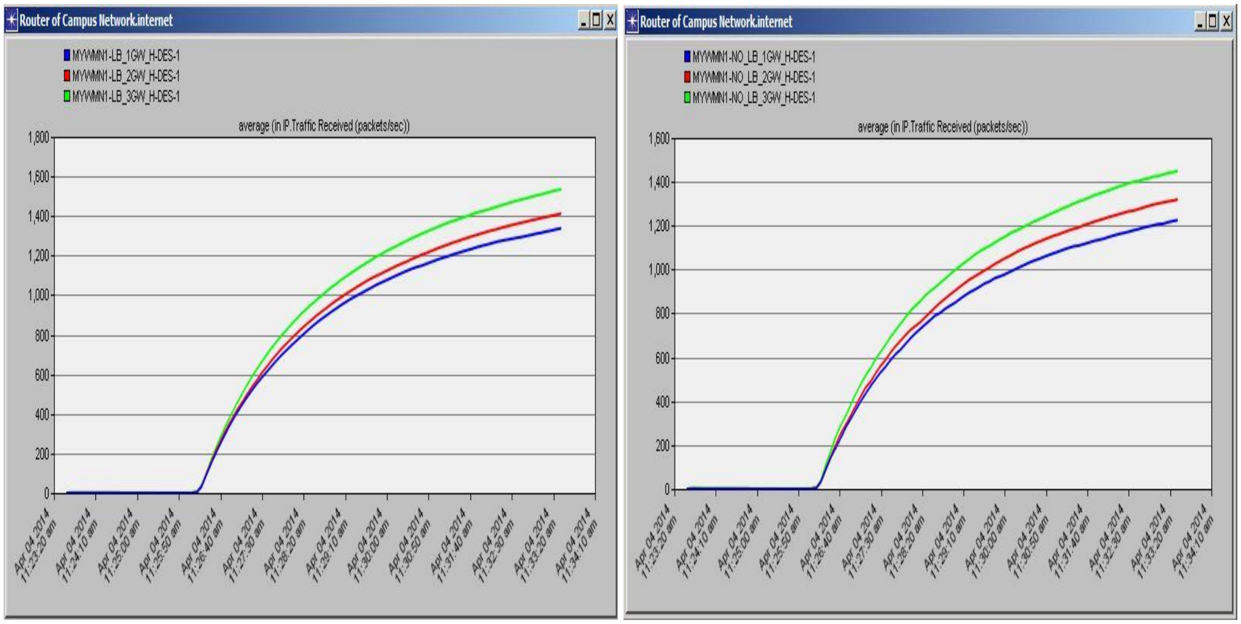


Figure 5.5.13 Throughput in Low Traffic LB_2GW Scenario and NO_LB_2GW Scenario



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.14 Throughput in High Traffic Scenarios

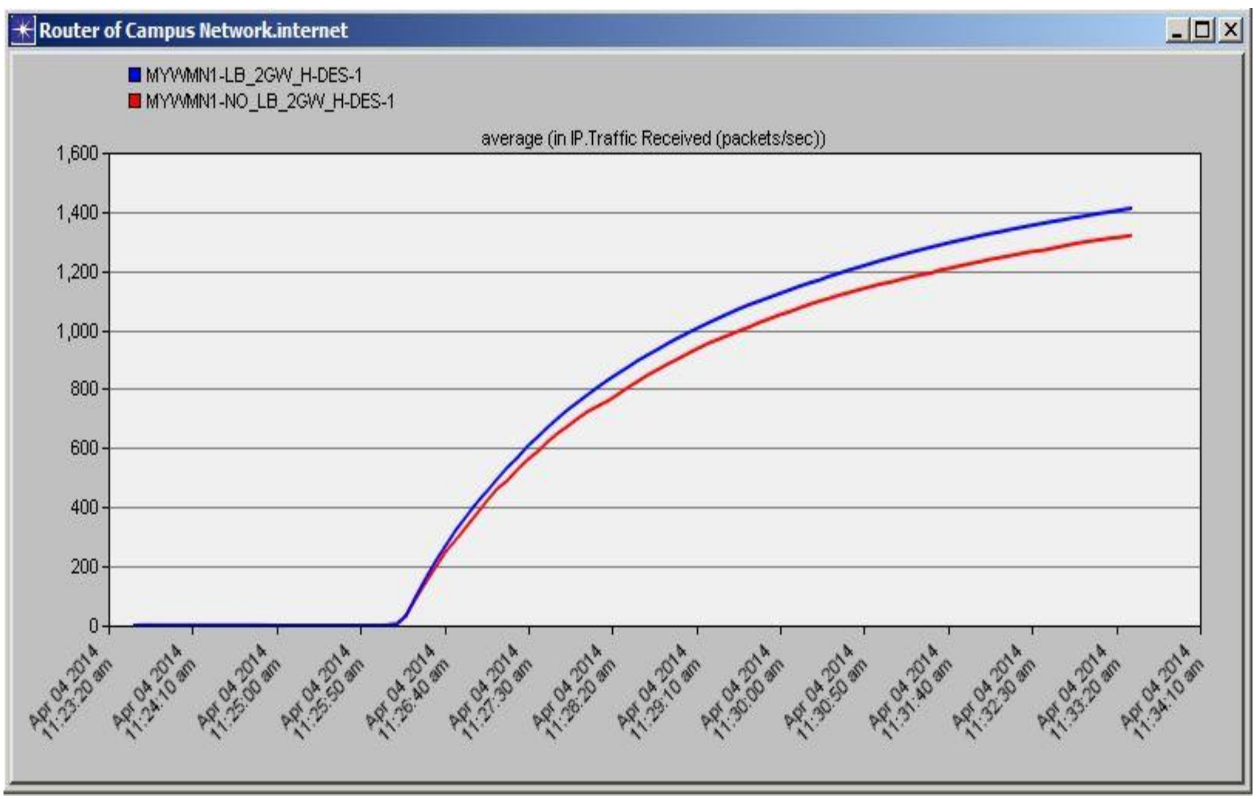
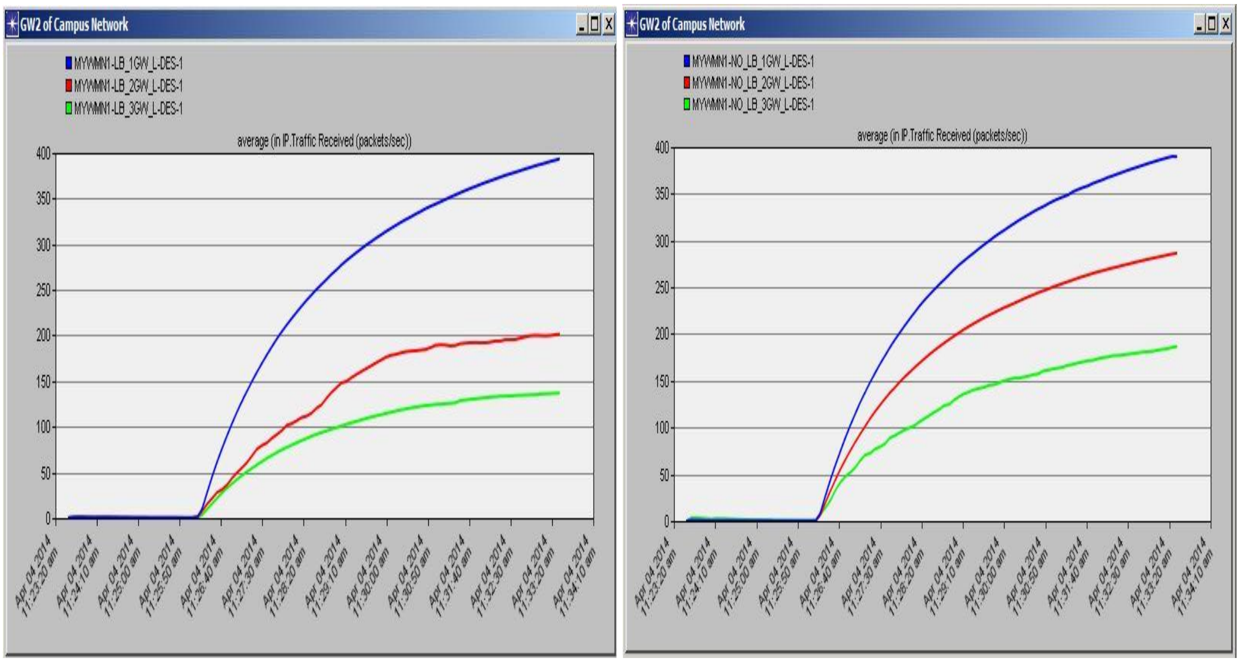


Figure 5.5.15 Throughput in High Traffic LB_2GW Scenario and NO_LB_2GW Scenario



a) LB Scenarios b) NO_LB Scenarios

Figure 5.5.16 Received Traffic in Gateway NO. 2 in Low Traffic Scenarios

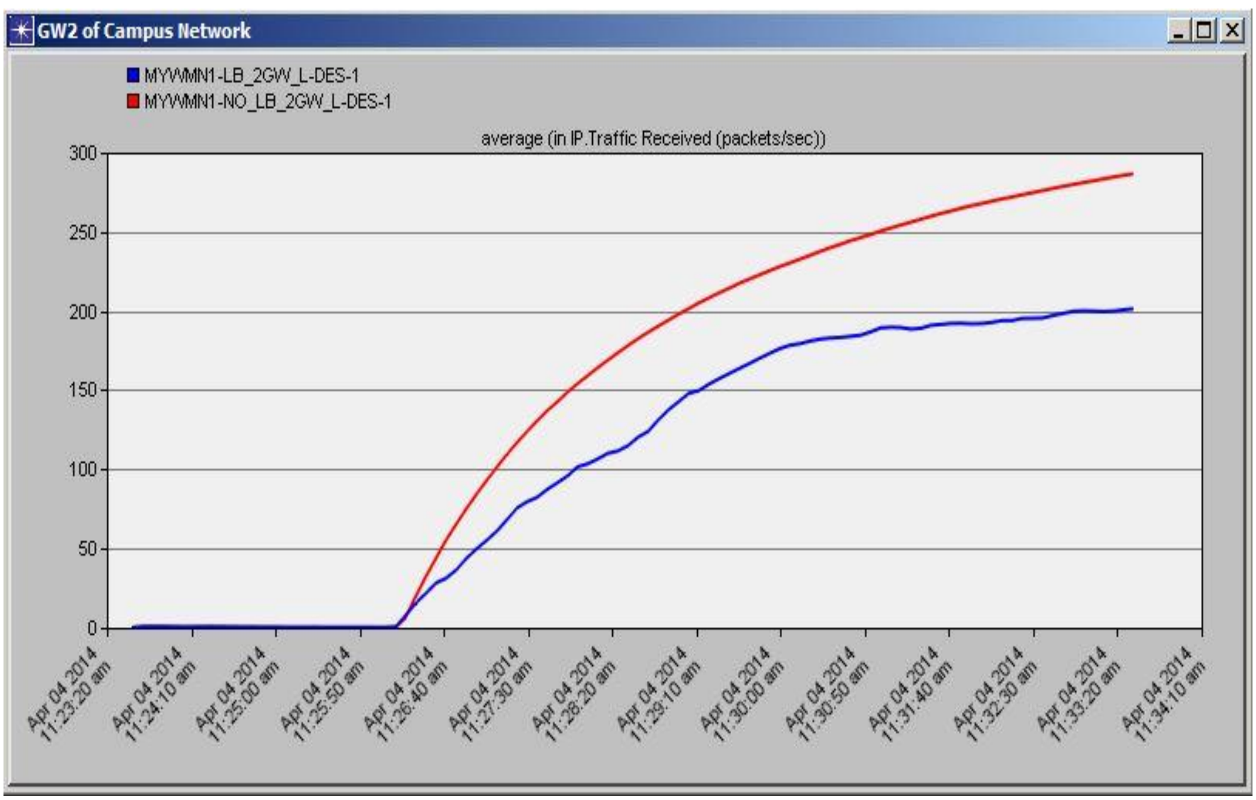
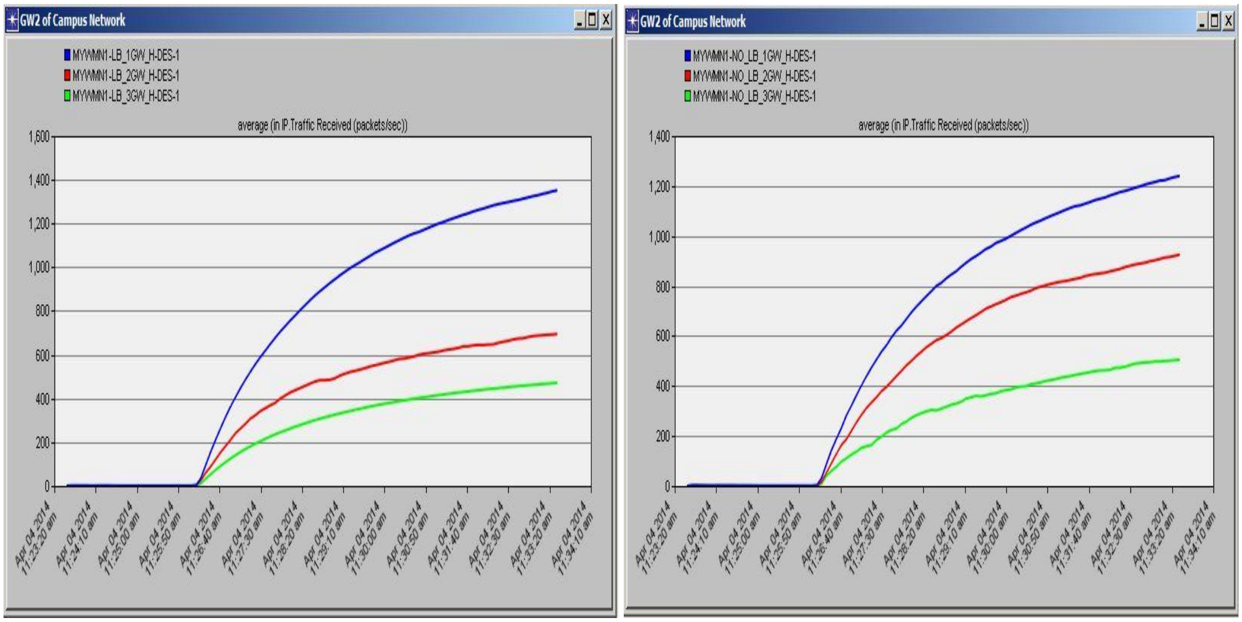


Figure 5.5.17 Received Traffic in Gateway NO. 2 in Low Traffic LB_2GW Scenario and NO_LB_2GW



a) LB Scenarios

b) NO_LB Scenarios

Figure 5.5.18 Received Traffic in Gateway NO. 2 in High Traffic Scenarios

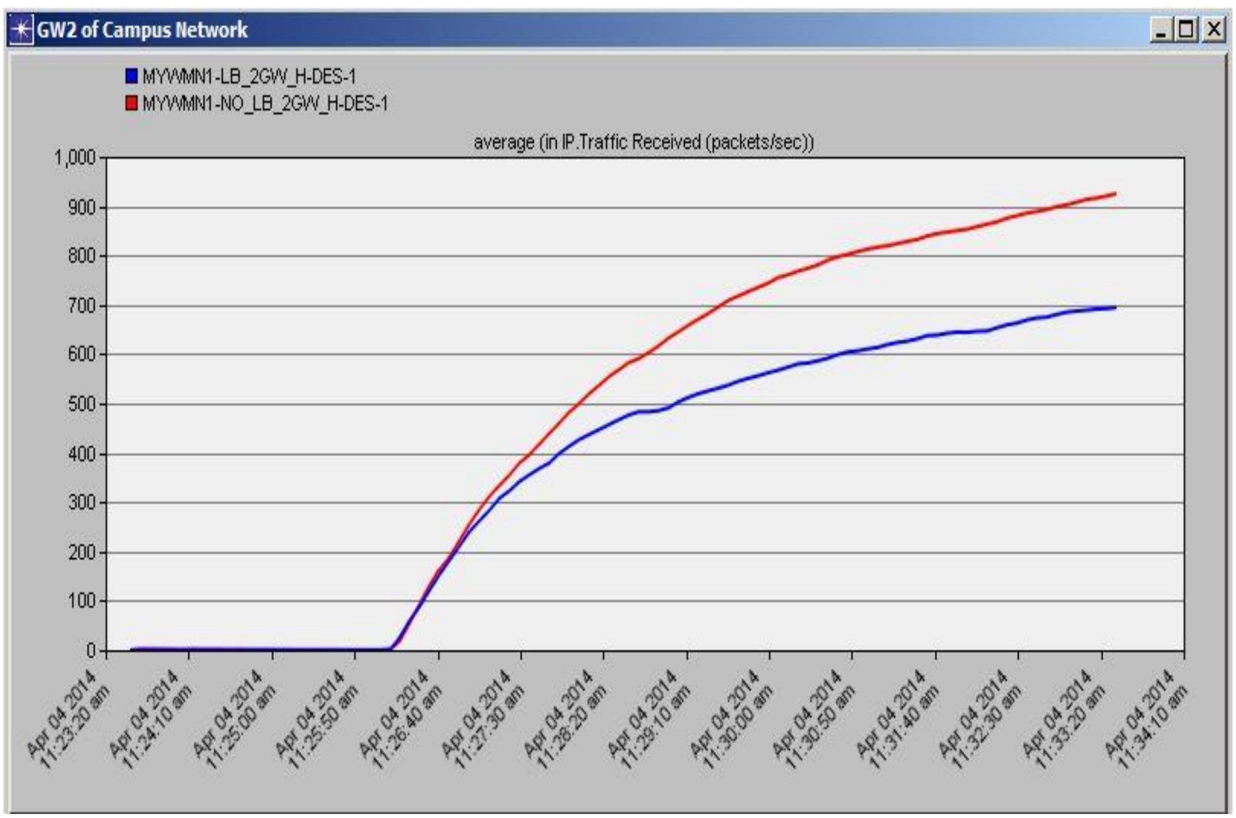


Figure 5.5.19 Received Traffic in Gateway NO. 2 in Low Traffic LB_2GW Scenario and NO_LB_2GW

As shown in figures (5.5.1-5.5.3) data drop rate is the data dropped by wireless Mac layer received from the upper layer due to buffer overflow. The average of dropped data in low traffic scenarios in both LB scenarios and NO_LB scenarios are same there is no data dropped, while when we increase the generated traffic data dropping has appeared and increased the scenarios without load balancing have the maximum number of data dropped as you see in figure (5.5.2). In NO_LB scenarios the routing protocol will select the shortest route so there is overloading and congestion in some routers and gateways the buffer will be overflow all the time that is why the rate of data dropped in NO_LB scenarios is the maximum. A lot of data dropped is unacceptable to any application running in the network so we have to minimize the rate of data dropped as possible as we can to optimize the mesh network performance. Increasing the number of gateways and make multiple routes with equal cost in the mesh network will optimize the data dropped rate in both LB scenarios and NO_LB scenarios.

As shown in figures (5.5.4-5.5.7) that the delay in low traffic NO_LB scenarios have the minimum delay. In high traffic scenarios, the LB scenarios have the minimum delay because in NO_LB scenarios, AODV will select the shortest routes then some of intermediate nodes will be used more than others and more traffic will pass through shortest route. The packets will take a lot of time waiting in buffer queue to be transmitted. In LB scenarios the traffic will be distributed in balancing between all available routes and nodes so the packets will take same time in buffer queue in every intermediate node until reaching its destination. Delay will be optimized by increasing the number of gateways in the mesh network will optimize the delay in both LB scenarios and NO_LB scenarios so scenarios with more routes and gateways will have a minimum delay.

As shown in figures (5.5.8-5.5.11) retransmissions Attempts statistics in OPNET shows the retransmission attempts by all the WLAN Mac layers until the packet is successfully reached the destination or discarded due reach its maximum retry limit. Figure (5.5.8) shows that LB scenarios have the minimum number of retransmission attempts comparing with NO_LB scenarios, because in NO_LB scenarios congestion in the network and buffer overflow problem will require the packet be retransmitted more times.

Figures (5.5.12-5.5.15) show us the throughput, in low traffic scenarios the throughput is equal because there is no data dropped in all low traffic scenarios, but in figure (5.5.14) in high traffic scenarios we can see that LB scenarios have the maximum throughput comparing with NO_LB scenarios.

Figures (5.5.16-5.5.19) show us the total received traffic in gateway number 2 (GW2) we easily observed that in LB scenarios the traffic was distributed in balancing between available gateways but in NO_LB GW2 received a lot of traffic comparing with other gateways because its position. We used same name GW2 for all scenarios for the same gateway and kept it in the same position.

Chapter6
Discussions of Simulation Analysis

6.1 Discussions of Simulation Analysis

Here are the overall OPNET Modeler 14.5 results, the final comparison and statistical information with respect to data dropped, delay, throughput, retransmission attempts, route discovery time, and survivability.

Performance Metrics	Low Traffic Scenarios					
	LB_1GW	NO_LB_1GW	LB_2GW	NO_LB_2GW	LB_3GW	NO_LB_3GW
Data Dropped (bits/sec)	0	0	0	0	0	0
Delay (sec)	0.00028	0.00017	0.00025	0.00015	0.00021	0.00013
Throughput (packets/sec)	400	400	400	400	400	400
Traffic Received in GW2 (packets/sec)	400	400	200	290	140	190
Retransmission Attempts (packets)	0.048	0.079	0.040	0.064	0.038	0.050
Route Discovery Time	0.04	0.18	0.04	0.18	0.04	0.18
Hops/Route	7	6	7	6	7	6
Survivability	Support	Support	Support	Support	Support	Support

Table 6.1.1 Overall OPNET Modeler 14.5 results of Low Traffic Scenarios

Performance Metrics	High Traffic Scenarios					
	LB_1GW	NO_LB_1GW	LB_2GW	NO_LB_2GW	LB_3GW	NO_LB_3GW
Data Dropped (bits/sec)	40000	90000	25000	70000	15000	45000
Delay (sec)	0.0054	0.023	0.0048	0.019	0.0028	0.016
Throughput (packets/sec)	1370	1210	1400	1360	1570	1420
Traffic Received in GW2 (packets/sec)	1370	1210	700	950	430	500
Retransmission Attempts (packets)	0.14	0.22	0.12	0.20	0.10	0.18
Route Discovery Time	0.1	0.35	0.08	0.30	0.07	0.27
Hops/Route	7	6	7	6	7	6
Survivability	Support	Support	Support	Support	Support	Support

Table 6.1.2 Overall OPNET Modeler 14.5 results of High Traffic Scenarios

6.2 Data Dropped

According to the tables (6.1.1-6.1.2), which are showing the behavior of the mesh networks, it is concluded that in the LB and NO_LB low traffic scenarios there is no data dropped appeared because the total generated traffic is less than the capacity of the mesh network, but in the LB and NO_LB high traffic scenarios when the generated traffic was increased data dropped appeared, NO_LB scenarios have the worst cases of data dropped because the congestion, time to live expiration, and buffer overflow in some intermediate mesh routers which were selected as the shortest route and used more than other routers, we noted that data dropped decreased when we increased the gateways but NO_LB scenarios still the worst comparing with LB scenarios . LB scenarios are the best because all the available routes are equal in cost, and the traffic was distributed in balancing between all routes. In order to optimize the data dropped rate in WMN, we have to decrease data dropped as possible as we can. We observed the optimization when we increase the number of gateways in mesh network to distribute the traffic between them. Establishing and using multiple routes with equal cost make the routing protocol implement the load balancing in professional method as we observed that LB scenarios are the best comparing with NO_LB scenarios.

6.3 Delay

In The case of WMN delay we notice from the tables (6.1.1-6.1.2) that in low traffic scenarios the NO_LB has the minimum delay comparing with LB scenarios because using shortest routing path minimize the required time to deliver the traffic, but in high traffic scenarios the NO_LB scenarios have the maximum delay comparing with LB scenarios because when the most of packets used shortest route this will produce congestion in this route and this will increase the waiting time in buffer queue, this is the main reason of delay in network. Increasing the traffic will increase the delay as we observe from the same tables (6.1.1- 6.1.2) but still NO_LB scenarios are the worst comparing with LB scenarios in high traffic scenarios. In LB scenarios, the routes cost is equal, so the traffic distributed in balancing between available routes. In order to optimize the delay in WMN, we have to decrease the delay as possible as we can. We observed the optimization when we increase the number of gateways in mesh network to distribute the traffic between them. Making and using multiple routes with equal cost make the routing protocol implement the load balancing in professional method as we observed that LB scenarios are the best comparing with NO_LB scenarios.

6.4 Throughput

Throughput is the successful delivering of the data over a communication network, and it is very clear from the tables (6.1.1-6.1.2) that the LB scenarios have the maximum throughput in high traffic scenarios but in low traffic scenarios all scenarios are same because the data drop rate is zero. When the flowing traffic in network more than the network capacity this will produce data dropping, the final delivery of the traffic over a communication network will be less than generated traffic. The total number of gateways in the mesh network affect the throughput more gateways give high throughput in both scenarios LB scenarios and NO_LB scenarios because the traffic will be distributed between available gateways. In order to optimize the throughput, we have to use LB technique to distribute the traffic between available routes and gateways, but with routes equal in cost and add more gateways as possible as we can.

6.5 Traffic Received in GW2

GW2 was used in all scenarios to observe the total traffic received by this gateway. In LB scenarios, we observed from the tables (6.1.1-6.1.2) that the traffic distributed in balancing between all gateways in LB_2GW and LB_3GW and the total received traffic are equal. In NO_LB scenarios, we found the opposite the most traffic was forwarded to GW2 because its position in shortest route so when we increase the number of gateways the received traffic was decreased but not same as in LB scenarios. In order to optimize the traffic received in GW2, we have to use LB technique to distribute the traffic in balancing between available gateways, but with routes equal in cost and add more gateways as possible as we can.

6.6 Retransmission Attempts

Retransmission Attempts is all attempts of the WLAN Mac layers until the packet is successfully reached the destination or discarded due to maximum retry limit. The LB scenarios have the best average of retransmission attempts, and we observed that when we increased the number of gateways the number of retransmission attempts was decreased because the traffic will be distributed through more than one gateway. In NO_LB scenarios, there is congestion in some intermediate routers and gateways so the average of retransmission attempts increased for the high average comparing with other LB scenarios this is because congestion and buffer overflow. In order to optimize the retransmission attempts, we have to use LB technique to distribute the traffic between available routes and gateways, but with routes equal in cost and add more gateways as possible as we can.

6.7 Route Discovery Time

Route discovery time is the needed time to find one route from the source node to the destination node. From tables (6.1.1-6.1.2), we observe that LB scenarios have the minimum route discovery time in low traffic scenarios and high traffic scenarios. Routing requests in multihop network will pass through many hops and every hop will take some time in checking the routing table to look for available route, if the route is available it will directly send the routing reply to the source node otherwise the hop will update its routing table and broadcast the RREQ again so the time of route discovery will increase when we increase the number of hops between the source node and distention node in mesh network. NO_LB has the big average of time because all clients in the start up of the network don't have routes so they will broadcast routing request in same time this will produce congestion in buffer of wireless interface of mesh router and intermediate hops that is why the average time in this scenario is larger than LB scenarios. In order to optimize the route discovery time, we have to use LB to distribute the routing requests between available equal routes and use more gateways as possible as we can.

6.8 Survivability

Survivability is the ability to remain alive and continue to deliver services and execute the function during the failure statement and errors. This feature is not available in any type of wireless network because there is only one route, one gateway, and limit number of intermediate routers, if there is a failure in one intermediate router or gateway the network will be down, and all the generated traffic will be dropped because all the packets will exceed the maximum number of retransmission attempts to sent the requests to gateways. The opposite happen in the mesh network scenarios because mesh network has multiple gateways and multiple routes from the sources node to the destinations node, this will insure that mesh network will be able to remain alive and continue to deliver services and execute its function during a failure because if one route is down all the traffic will be forwarded through another route then the clients will never feel about this failure. In order to optimize the survivability, we have to use a mesh network with LB with multiple routes equal in cost to distribute the routing requests and traffic in balancing between available routes and gateways.

Chapter7

Fuzzy Load Balancing

7.1 Fuzzy Load Balancing

Routing process in WMN is the best topic to optimize the network performance. The proposed work in this research aims to optimize the routing process decisions in AODV routing protocol to achieve the goals of this research which are maximizing the throughput, minimizing the delay, and implementing load balancing technique in the mesh network.

7.2 Basic Assumptions

1. All gateways and mesh routers were deployed in fixed position, they are not mobility.
2. Every mesh router has more than one connection to its neighbors.
3. All the mesh routers that are used for mesh client's connections use same radio frequency, and same SSID.
4. Mesh routers that are using many wireless interfaces can use different radio frequency, different channels, and different SSID.
5. Omni antenna is used for mesh clients connections, and sector antenna is used for mesh router connections.
6. Mesh clients can connect to any mesh router.
7. AODV was used as a routing protocol in this network.
8. Load balancing technique was implemented to insure bandwidth utilization and fault tolerance.

7.3 Fuzzy Routing

In WMN there are many constraints like interference, bandwidth, hop count, buffer utilization, signal strength, etc. need to be taken into account in routing decisions, also if there are many routes to same destination make routing decisions be more difficult.

Fuzzy logic controller was used to make the routing decision and bandwidth allocation. We selected three routing decision constraints hop count, buffer utilization, and signal strength. Fuzzy logic was used in this research to make optimal routing decisions and bandwidth allocation which is decided based on the metrics between routes. Fuzzy logic has three main components which are:

1. Fuzzification (Input)

2. Knowledge base (Rules)

3. Defuzzification (Output)

7.4 Fuzzy Routing Constraints

There are three input parameters are used to make fuzzy-rule sets

1. Hop Count: In general, a lower number of hops per route mean this is the shortest route to the destination.
2. Buffer Utilization in next router: In general, so many packets in the buffer of the router this mean that the current load of the router is high, using overloading router as an intermediate router will increase the delay and the number of data dropped.
3. Signal Strength: signal strength indicates the quality of the link between routers in that route, so next router with a strong signal is the best choice to use it to forward the packets.

Every mesh router has to keep in its routing table the next mesh router metrics (hop count, buffer utilization, and signal strength). The route with high probability to send represents the quality of communication link and route to handle new data transmitting. Buffer utilization and signal strength are used to select the next router in the route, but hop count means how many hops between the source node and the destination node.

Route probability to send represents the routing decision method where route with high probability will be selected as the optimal route. The value of the probability is between 0 and 1

($0 \leq \text{Prob.}_{\text{R}} \leq 1$).

If ($\text{Prob.}_{\text{R}_\text{x}} > \text{Prob.}_{\text{R}_\text{Y}}$) Then (R_x) is the optimal route where R is route and X is Router X.

There is one important process is executed before making routing decision, it is fuzzification process which takes the inputs at each router and insert it into fuzzy inference engine to scan through the fuzzy rules to find the suitable value for fuzzy inputs to calculate the fuzzy output cost for each router. Every fuzzy input has membership functions represent the fuzzy subsets of the input. In this work we used three fuzzy inputs hop count, buffer utilization, and signal strength. The fuzzy inputs have been divided into three fuzzy subsets (Low - Medium - High). fuzzification process is used to map the fuzzy inputs to a crisp value between (0,1) using triangular membership.

7.5 Membership Function and Fuzzy Rule Base

The degree of truth is represented by the membership function of a fuzzy set, so any fuzzy input has fuzzy subsets. We divided the inputs into three subsets - low, medium and high. The figure (7.5.1) is used to map the real-world fuzzy inputs to the range [0…1]. The fuzzy grade was given from fuzzy rule base using fuzzy inputs. The fuzzy grade tells which route is the optimal. We used IF, AND operator and THEN in fuzzy rule base to get on fuzzy grade as shown in the tables (7.5.1-7.5.3).

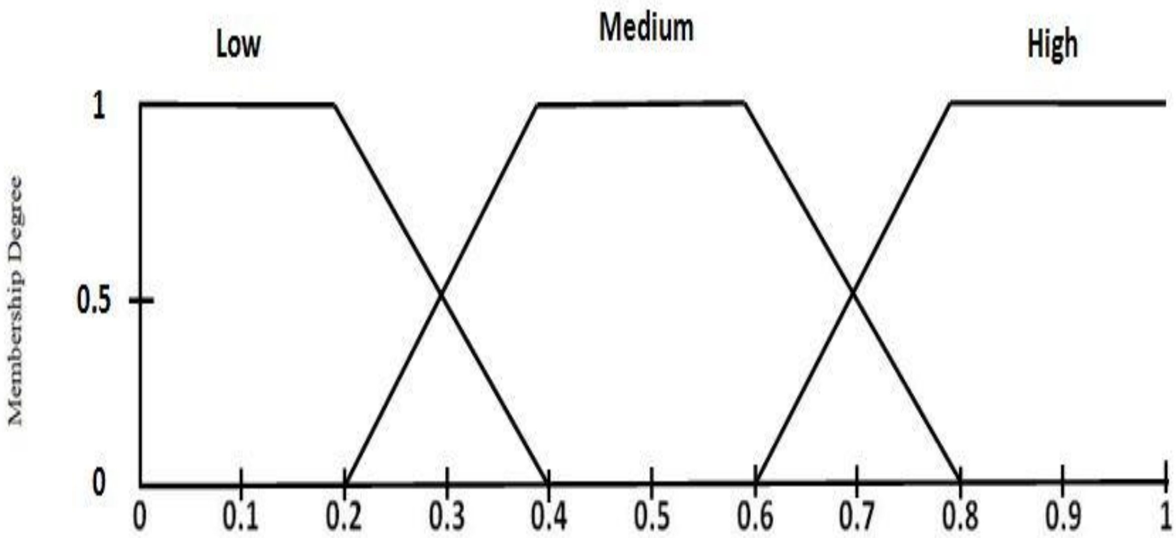


Figure 7.5.1: Membership function of input parameters

Signal Strength is high			
Hop \ **Butz**	**High**	**Medium**	**Low**
High	**0.08**	**0.30**	**0.60**
Medium	**0.20**	**0.50**	**0.80**
Low	**0.30**	**0.60**	**0.92**

Table: 7.5.1: Rule base for fuzzy system when Signal strength is high.

Signal Strength is medium			
Butz / Hop	High	Medium	Low
High	0.05	0.25	0.45
Medium	0.08	0.35	0.65
Low	0.25	0.45	0.82

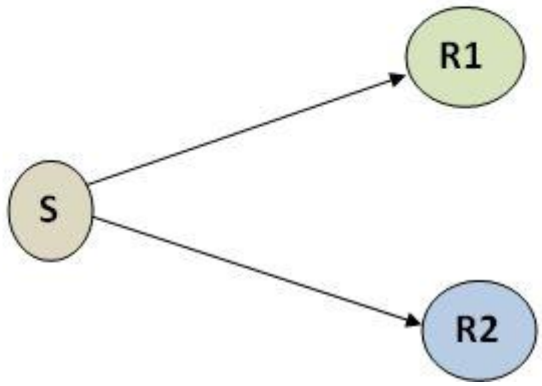
Table: 7.5.2: Rule base for fuzzy system when Signal strength is medium.

Signal Strength is low			
Butz / Hop	High	Medium	Low
High	0.02	0.20	0.40
Medium	0.05	0.30	0.60
Low	0.20	0.40	0.80

Table: 7.5.3: Rule base for fuzzy system when Signal strength is low.

7.6 Examples

In this example as shown in figures (7.6.1-7.6.3) we have one router (S) connected to two other routers (R1 and R2), both routers can reach the destination, there are two routes to forward the traffic, we will use our proposed work to make the correct routing decision regarding to fuzzy logic rules in previous tables. The challenge of fuzzy logic system is when the values comes in cross area between two fuzzy logic subset, then the output value will be not clear because it is not 100% low, medium, or high because it is in between them, here we define new calculation process to get on the correct value of fuzzy logic. If the value 100% Low, 100% medium, or 100% high it is easy to calculate the output value. The following example will explain how to calculate the probability to send between two routers supposing the two routers will forward the coming traffic to the same destination.



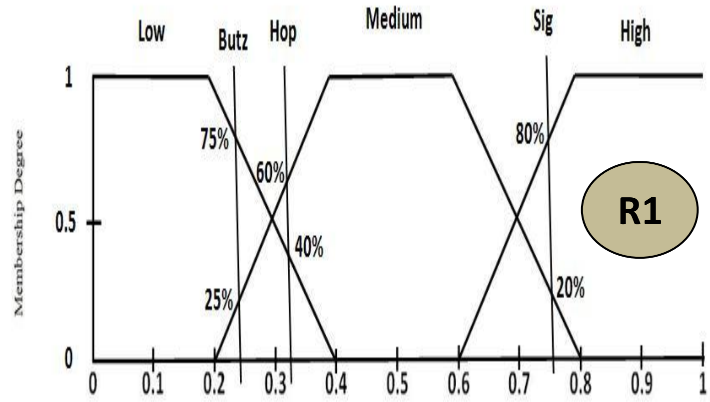


Figure 7.6.1: Two routes to forward traffic to gateway   Figure 7.6.2: Fuzzy logic input parameters of R1

Probability to send through R_1 in figure (7.6.1) regarding the fuzzy parameters values in figure (7.6.2), all values were extracted into the table (7.6.1)

Parameter	**Value**	**Membership degree**		
		Low	**Medium**	**High**
Signal strength	0.77	0%	20%	80%
Hop	0.32	40%	60%	0%
Buffer utilization	0.25	75%	25%	0%

Table 7.6.1: Fuzzy logic input parameters values of R1

$$\text{Prob. R1} = (Sig_{\max}\big((prob._{HMM} * Hop_M * Butz_M) + (prob._{HLM} * Hop_L * Butz_M) + (prob._{HML} * Hop_M * Butz_L) + (prob._{HLL} * Hop_L * Butz_L)\big)\big) + (Sig_{min}((prob._{MMM} * Hop_M * Butz_M) + (prob._{MLM} * Hop_L * Butz_M) + (prob._{MML} * Hop_M * Butz_L) + (prob_{MLL} * Hop_L * Butz_L\ ))$$

Where:

1. $Sig_{\max}$ is the maximum value of signal strength regarding to what area it is in high, medium, or low, it is 80% in high area in this example.
2. $prob._{HMM}$ is the probability to send from table (7.3.1) when signal is high, hops is medium, and buffer utilization is medium it is (50%).
3. Hop_M is the value of hops in medium area, it is (60%).
4. $Butz_M$ is the value of buffer utilization in medium area, it is (25%).
5. $Sig_{\min}$ is the minimum value of signal strength regarding to what area it is in high, medium, or low, it is 20% in medium area in this example.

This process will be repeated for all values to get on the probability to send the value.

Prob. R1 = (0.8*((0.5*0.6*0.25)+(0.6*0.4*0.25)+(0.8*0.6*0.75)+(0.92*0.4*0.75)))

+ (0.2*((0.35*0.6*0.25)+(0.45*0.4*0.25)+(0.65*0.6*0.75)+(0.82*0.4*0.75)))

= 0.74

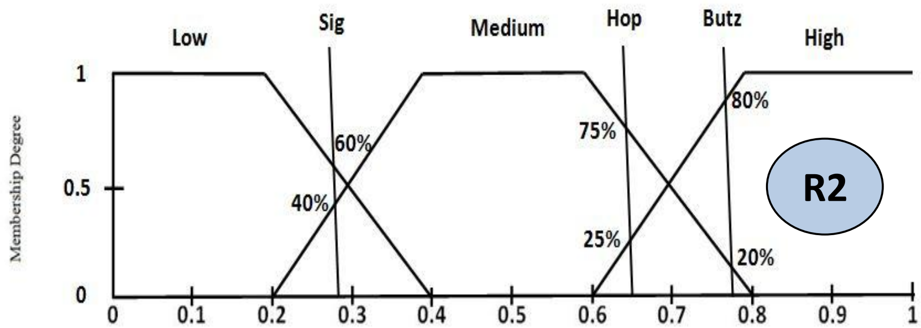


Figure 7.6.3: Fuzzy logic input parameters of R2

Probability to send through R2 regarding the fuzzy parameters values in figure (7.6.3) which were extracted to the table (7.4.4).

Parameter	**Value**	**Membership degree**		
		Low	**Medium**	**High**
Signal strength	0.28	60%	40%	0%
Hop	0.65	0%	75%	25%
Buffer utilization	0.78	0%	20%	80%

Table 7.6.2: Fuzzy logic input parameters values of R2

Prob R2 =(0.6*((0.3*0.75*0.2)+(0.05*0.75*0.8)+(0.2*0.25*0.2)+(0.02*0.25*0.8)))

+ (0.4*((0.35*0.75*0.2)+(0.08*0.75*0.8)+(0.25*0.25*0.2)+(0.05*0.25*0.8)))

= 0.103

Regarding the (Prob. R1) and (Prob. R2) we found the final results same as shown in table (7.6.3).

Prob. R1	**Prob. R2**
0.74	**0.103**

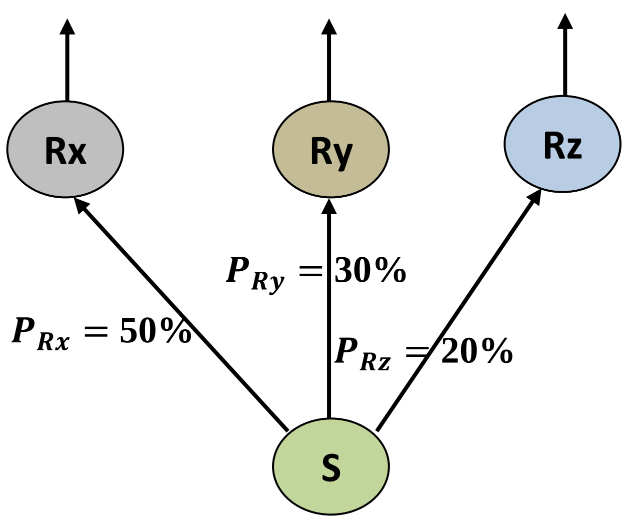
Table 7.6.3: The probabilities to send through two routers (R1, R2)

Then the probability to send through R1 is higher than the probability to send through R2. Then R1 will be selected as the optimal route to forward the traffic.

7.7 Proposed Fuzzy System for Load Balancing

We suggested new method for load balancing in WMN using fuzzy logic system. In pages (52-57) we explained how to use fuzzy logic system to make the routing decision and select the optimal route to the distention but now we improved and optimized the same work to implement load balancing technique in WMN. Per connection load balancing technique was used in this thesis so any new routing request comes to any mesh router it will check the routing table entries and compare between available next routers regarding to fuzzy base rules, the router with high value of probability to send will be used to forward the routing request and main route will be established. Same process will be repeated for every new routing request and comparison process will be run again to select the next router regarding the fuzzy base rules. During the running of the network the behavior of routers will change and the router with high value of the probability to send will change then new route will be selected as the optimal route and so on. Every 1,000 Milliseconds routers will exchange the information about previous three parameters (signal strength, hop count, and buffer utilization) to update the routing table entries using hello message, so any router received hello message will check the fuzzy base rules and compare between available routes to forward the next new routing request to optimal route, also to shift some clients from overloaded routes to un overloaded route.

Example of using fuzzy logic in routing load balancing where $P_{Rx} = 0.5$ mean that the probability to send through router (Rx) is (0.5) as shown in figure (7.5.1) and table (5.7.1).



Router	Probability to send
X	0.5
Y	0.3
Z	0.2

Table 7.7.1: Values of load balancing example

Figure 7.7.1: Load balancing example.

Then the traffic will be distributed as following :

1. 50% of connections will pass through router (Rx)
2. 30% of connections will pass through router (Ry)
3. 20% of connections will pass through router (Rz)

These values will change during the running of the network and the forward traffic also will be changed so this distribution of traffic will change regarding the new value of fuzzy logic system. Intermediate routers overloading problem, we proposed to define the maximum buffer utilization value for every mesh router. Any router reaches its maximum buffer utilization will broadcast hello message to warn its neighbors to stop sending any new routing requests to it, because it will drop and new routing request reaches it. When the buffer utilization of the overloading router changed again the router will broadcast new hello message to its neighbor by new changing. Suppose that in figure (7.7.1) (Rx) reach its maximum buffer utilization then router (S) will never use it until it notify its neighbors that its buffer utilization value changed, then it will be used again same as shown in figure (7.8.2).

7.8 Our Approach Steps

1. Modify the routing table to keep the probability to send through every route.
2. Every router in the network must keep and regularly update the probability to send values for all active routes.
3. Every router must apply the fuzzification on the three metrics and compare between the outputs of all available routes and sort routes regarding to probability to send.
4. Router with high probability to send will be selected as a next router to forward the traffic.
5. For simplicity and speed up the computing the probable next router we omit the defuzzification step and change the rule base to contain the properly selected crisp values instead of the fuzzy values.
6. As shown in figure (7.8.1), modify the RREQ packet to include on current buffer utilization for next router.
7. Every new node wants to send data will broadcast routing request to discover the route. During passing the RREQ packet through each router buffer utilization constraint will be measured and updated.
8. The fuzzy logic inputs will be fid into the fuzzy inference engine which decides the fuzzy grade of that router with the help of the fuzzy rules base which were given in Tables (7.5.1-7.5.3).
9. The destination node will receive the same RREQ but from different routes and send back RREP, we force the nodes to wait until receiving all RREQ and read the values of

three metrics and compare between these values. In order to achieve the optimization, route with high probability will be selected to send back the RREP.

10. As shown in figure (7.8.3), routers behavior will be changed without warning so we used hello message to update the three metrics continuously.

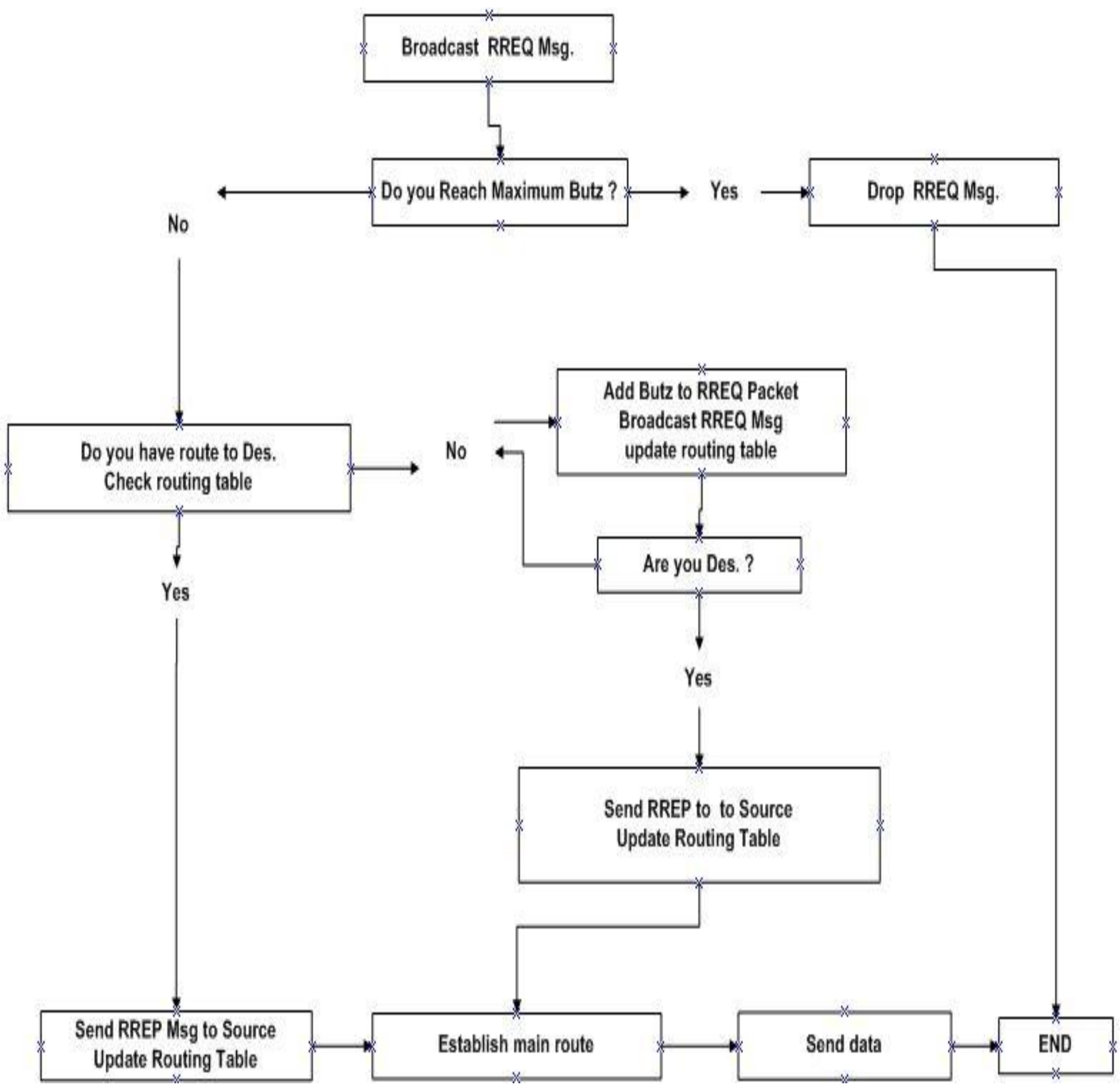


Figure 7.8.1: Modified RREQ Flowchart

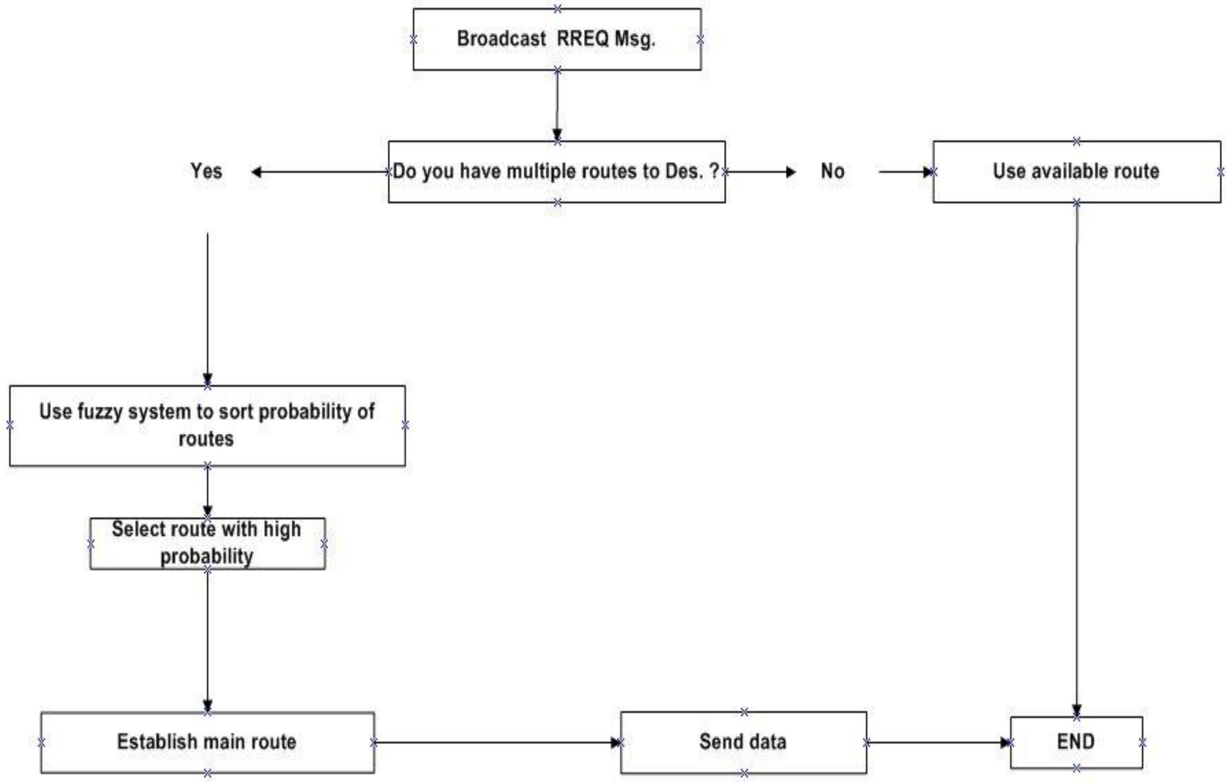


Figure 7.8.2 New Method Load Balancing

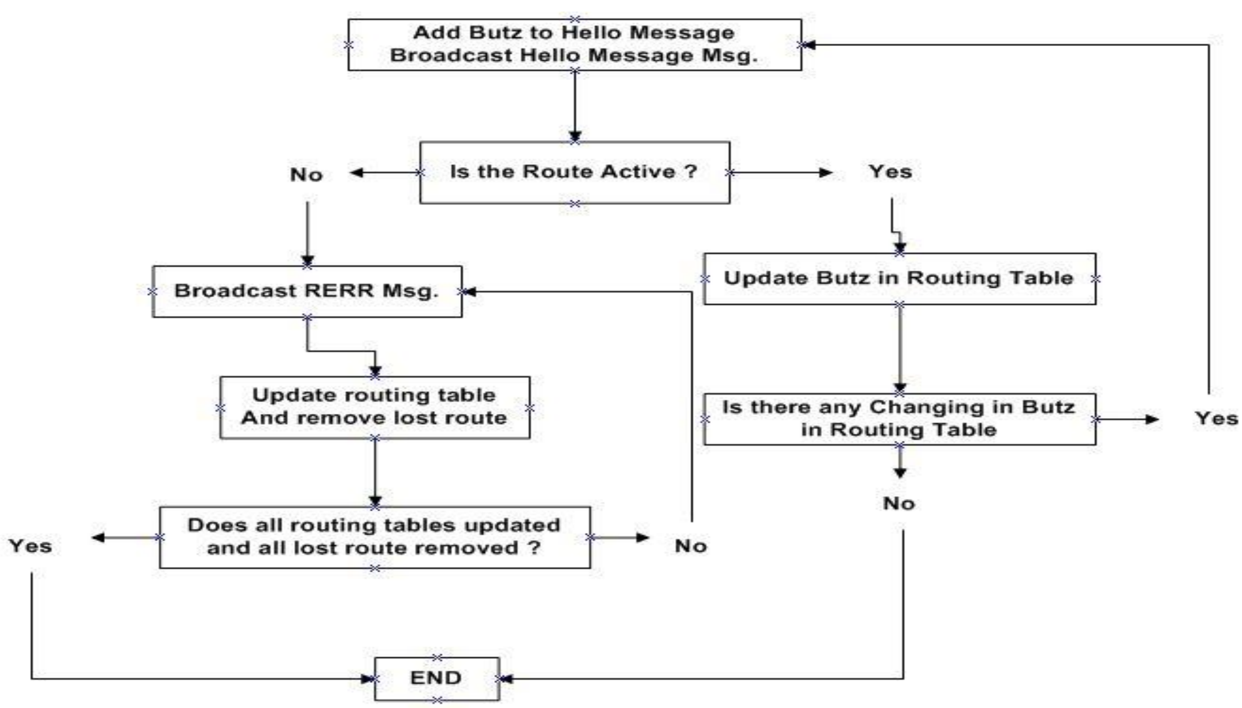


Figure 7.8.3: Modified Hello Message Flowchart

Chapter 8
Conclusion and Future Work

8.1 CONCLUSION

Nowadays, as the number of wireless traffic generated by the applications and users increases, routing optimization and bandwidth allocation need to be improved. Regarding the current and future research of WMN, I have studied few protocols to address these problems.

In this thesis, I investigated the routing optimization which provides the better bandwidth in WMN. Here, I modified existing routing protocol which is relevant to solve our basic network problems through the optimization. Fuzzy logic is a proper approach to be used in making routing decisions; we have to add and combine it with routing protocols in WMNs.

Experiment results show that the load balancing integrated with routing protocol helps us to improve the optimization. Basic network problems considered for overall performance and optimization in WMN are analyzed with and without load balancing. In this research, WMN works correctly with using load balancing in symmetric WMN and using routes equal to cost and to use more gateways as possible as we can. The optimizations should be fixed for individual network problems, applications, environments, etc.

8.2 Future Work

WMN is useful technology in the communications field, because it has great features, and it is the best choice to provide users with wireless internet access. Routing process and bandwidth allocation have the great impact on mesh network performance, still there are many challenges need to be optimized.

Mesh network has many routes from same source node to the destination node. In case of using one of these routes as a main route and the others used as backup routes, we need to optimize. Here, the time of shifting to another route is considered as a main route when there is a failure or interference in the main route.

Interference is the biggest challenge in WMN we need to optimize the challenge by minimizing the interference as possible as we can.

Further performance analysis of WMN with changing in WMN architecture and topology.

Implementation of WMNs in Saudi Arabia faces a big problem because temperature is very high. So, the performance of the mesh network in time from 10 PM to 4 AM be very low. This make many problems between clients and wireless internet services providers. So, it is good research area to find a solution to this problem and how to optimize the ability of mesh devices to bear high temperature.

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Appendices

Appendix A

WMN Implementation

This chapter will explain the implementation of WMN and its routing protocols in the simulation environment of OPNET modeler 14.5. The implementation will reflect the methodologies and objectives explained in this thesis. The reason for choosing the OPNET modeler simulation environment for this project will be discussed with the brief overview of the OPNET modeler 14.5. In this implementation, we have introduced the fuzzy logic technique to analyze the optimization problems. The step by step approach for the network design and configuration for various mesh routing protocols with snap shots will be provided.

Network Simulation

Current network architectures are very complex. Data center network contains thousands of servers. It's not possible to implement the network physical and then rebuild it again if the network performance is not suitable. The evolution of high power full computers and simulators made it possible to simulate these complex networks with realistic approach and results. There are two methods of computer network simulation; one is analytical modelling, and the second one is machine base simulation modelling. Analytical modelling model the network by set of mathematical equations. The disadvantage of this modelling is too much simplicity, and it cannot model the dynamic nature of the network. No such network exists today where fault and changes don't occur so to model the complex dynamic networks discreet event simulation (DES) engine is required which model the time event related to real time events in the network world. Software packages for network simulation for research and practical purpose are very important today because network is the critical part of every organization, and every organization has specific budget for network equipment, so it is always the feasible way to know about the behaviour of network inside the simulation environment and then make an investment on it.

DES software provides the programmer interface to model new ideas and protocols. Protocols and functions are working as finite state machine, as native programming code or a combination of these two. [33]

OPNET Simulator

Optimized Network Engineering Tool (OPNET) provides a DES environment for modelling the real world network and analyse the results for various performance parameters. OPNET supports a large set of network environments from a simple LAN network to satellite communication. OPNET comes with rich tools and model which give network experts and researchers a standardized environment to effectively study the effect of different network behaviours before deployment in the real world with simple steps same as shown in figure (A.1). The most important features of OPNET are given below. [39]

- Modeling and simulation feature of OPNET give the user a framework to first built the model, execute it and then analyze the results.

- OPNET has a hierarchical structure, each layer of an OPNET has its own set of parameters and characteristics.
- OPNET come with rich models of library with all world leading network hardware manufacturer devices and all available protocols and also provide programming interface to develop new protocols for the researchers.

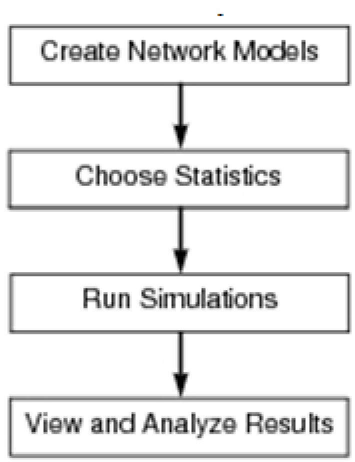

Figure A.1 OPNET Simulation Steps

OPNET Hierarchical Modeling

OPNET provides sets of editors in a hierarchical manner to model the network. These models work from low level programming language to higher level GUI. The model in each level can be access by its upper level. The basic editors in OPNET are the following:

Network Editor

The top editor is the network editor where the actual network architecture is deployed, and it consists of routers, switches, etc. It can model complex network in term of sub network which can be office network, enterprise network or the network through specific area of the world. All the low level models can be access from the network editor. A network editor is shown in the figure (A.2).

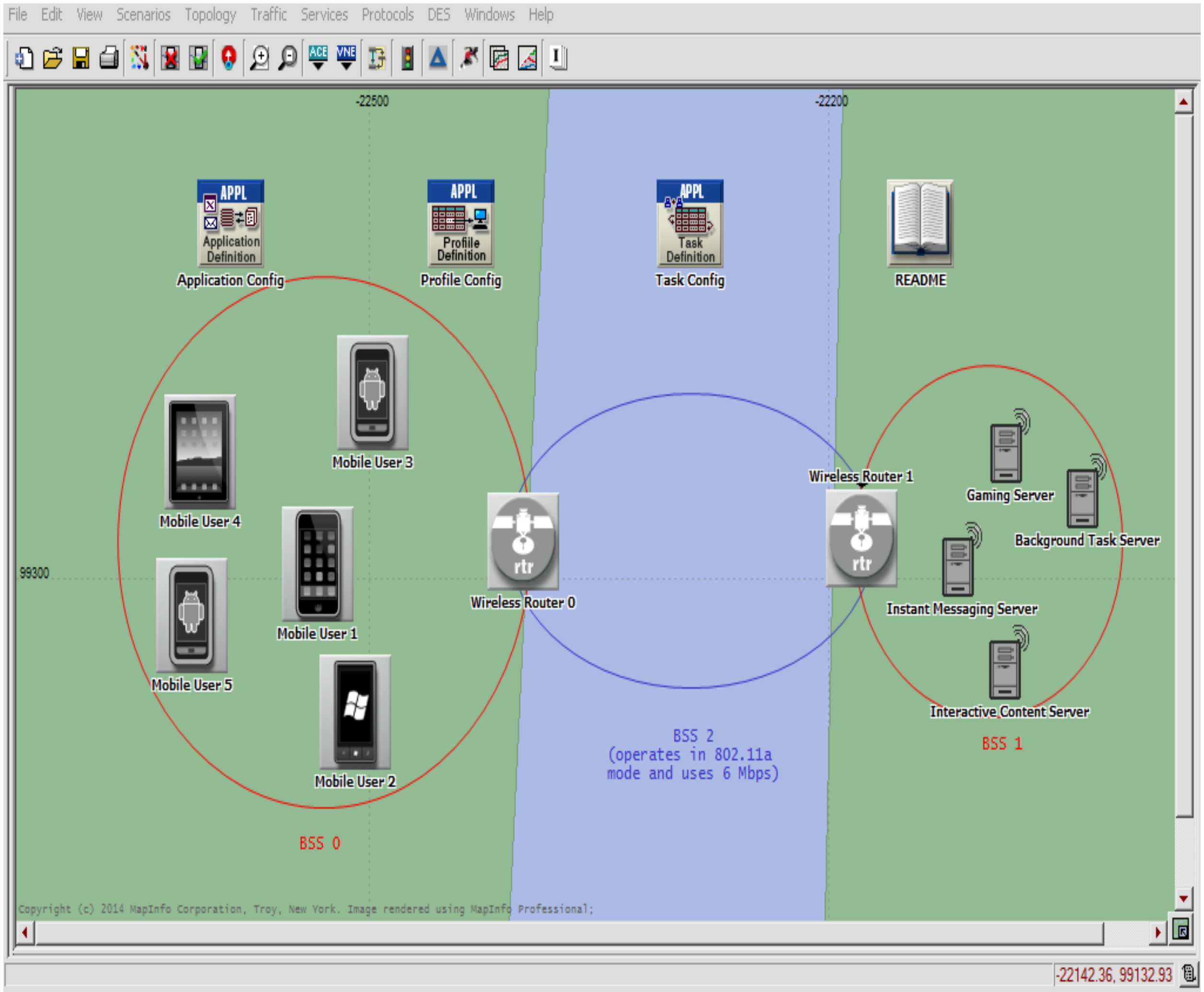

Figure A.2 Network Editor

Node Editor

Node editor specifies the behavior of each node inside the project editor. The behavior is defined in term of different modules. Each module specifies a unique behavior of the node like data creation, storage, transmission, etc. The node model is shown in the figure (A.3).

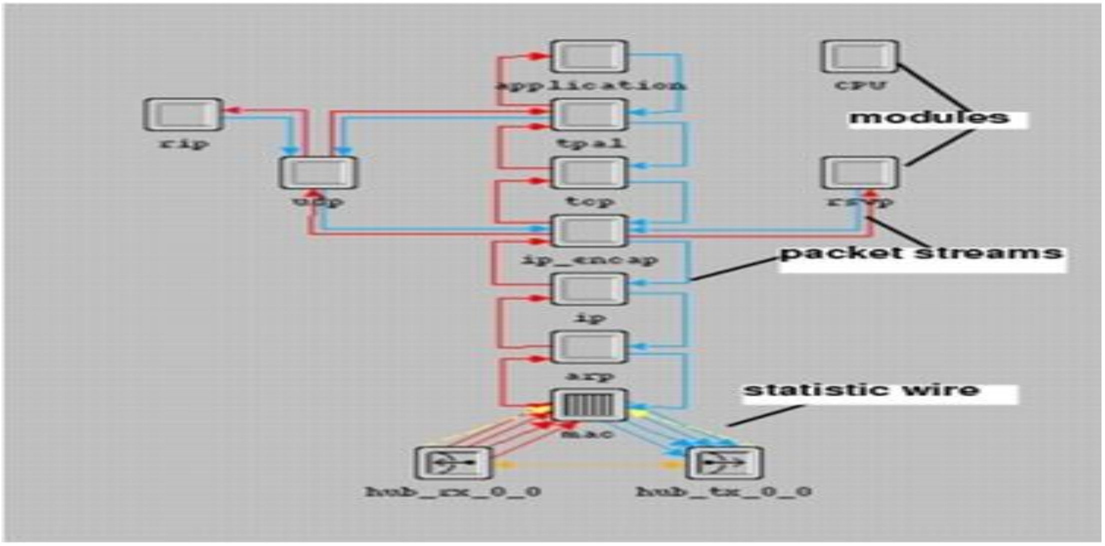

Figure A.3 Node Editor

Process Model Editor

The process model provides the editor to create different processes that run by the node created in the node editor. OPNET DES engine works on finite state machine (FSM) which is developed in the process model. The operation runs in each state are control by C and C++ as shown in the figure (A.4).

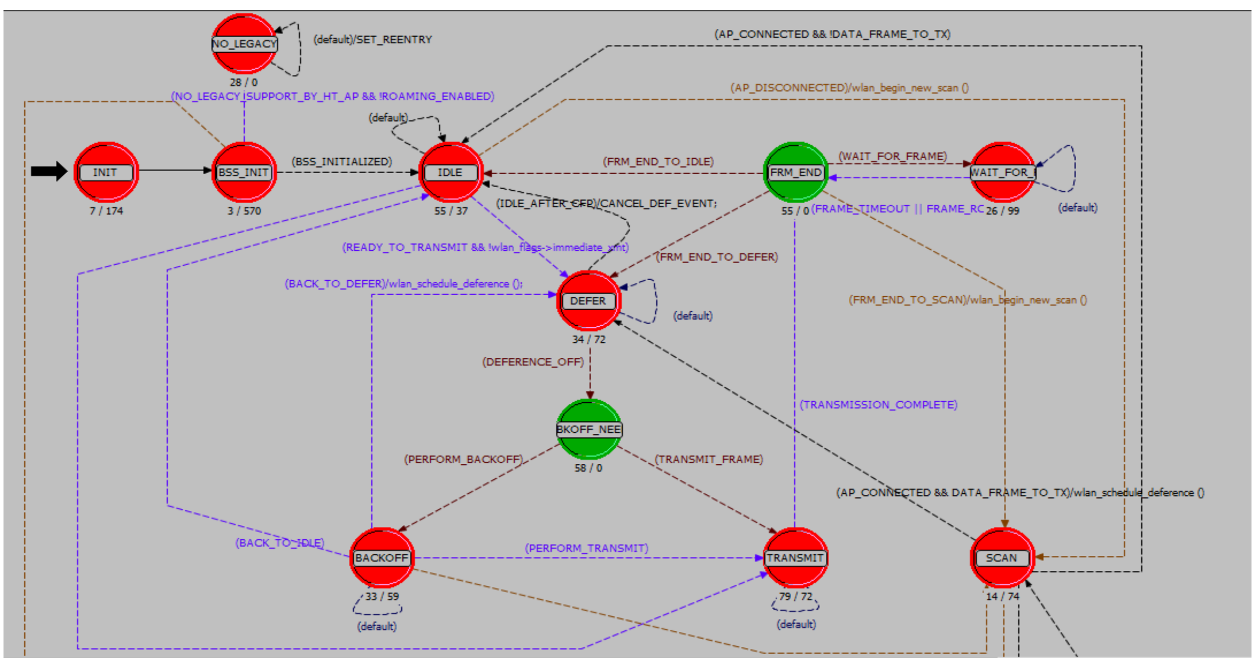

Figure A.4 Process Model Editor

Link Model Editor

Link model specify different attributes to link or to develop a new link model with specific defined parameters. The link editor model is shown in the **Error! Reference source not found.**(A.5).

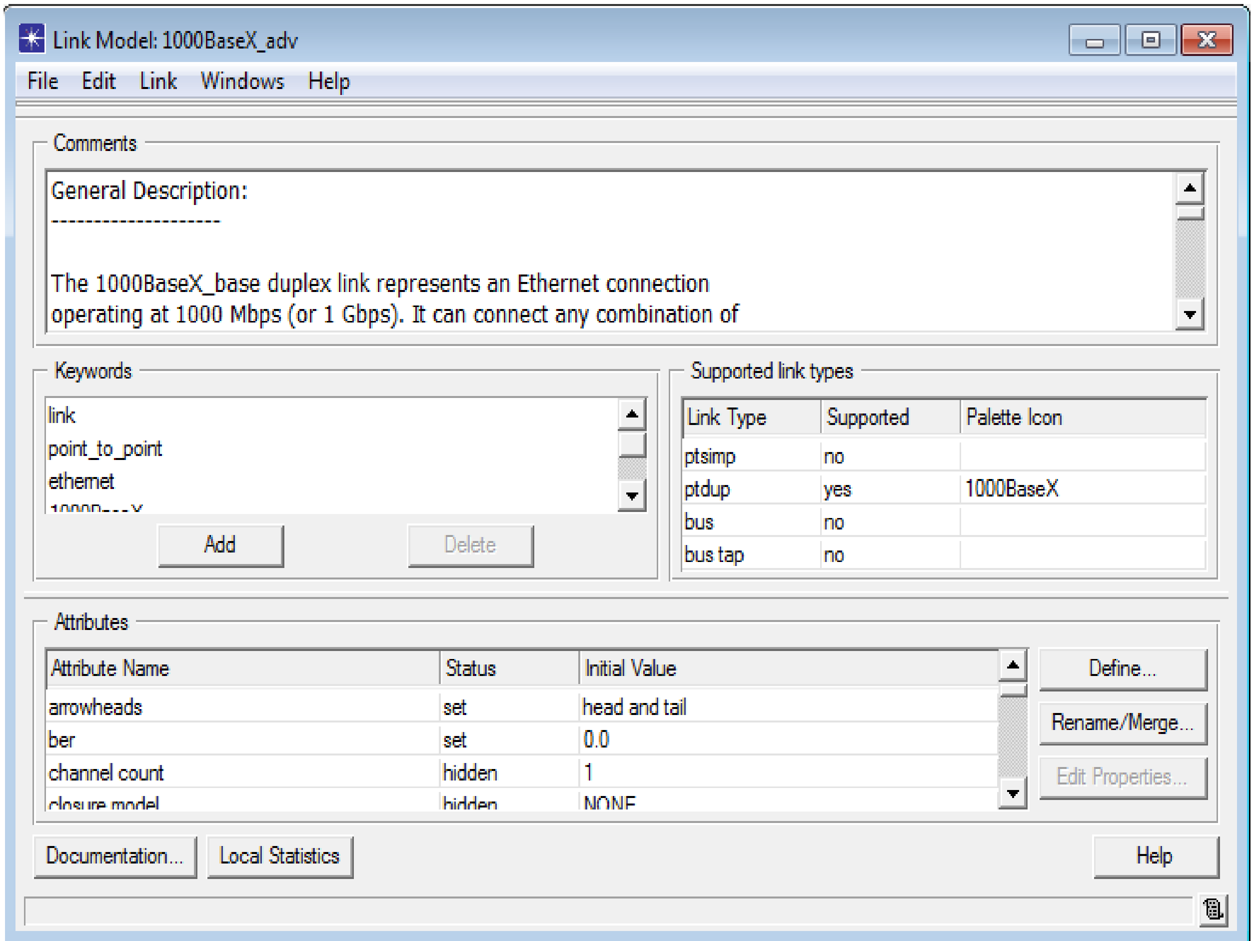

Figure A.5 Link Model Editor

Path Editor

New path route can be defined using this editor. All protocols which are using virtual circuits or logical circuits can use paths to route traffic. The path editor is shown in the **Error! Reference source not found.**(5.4.5.1)

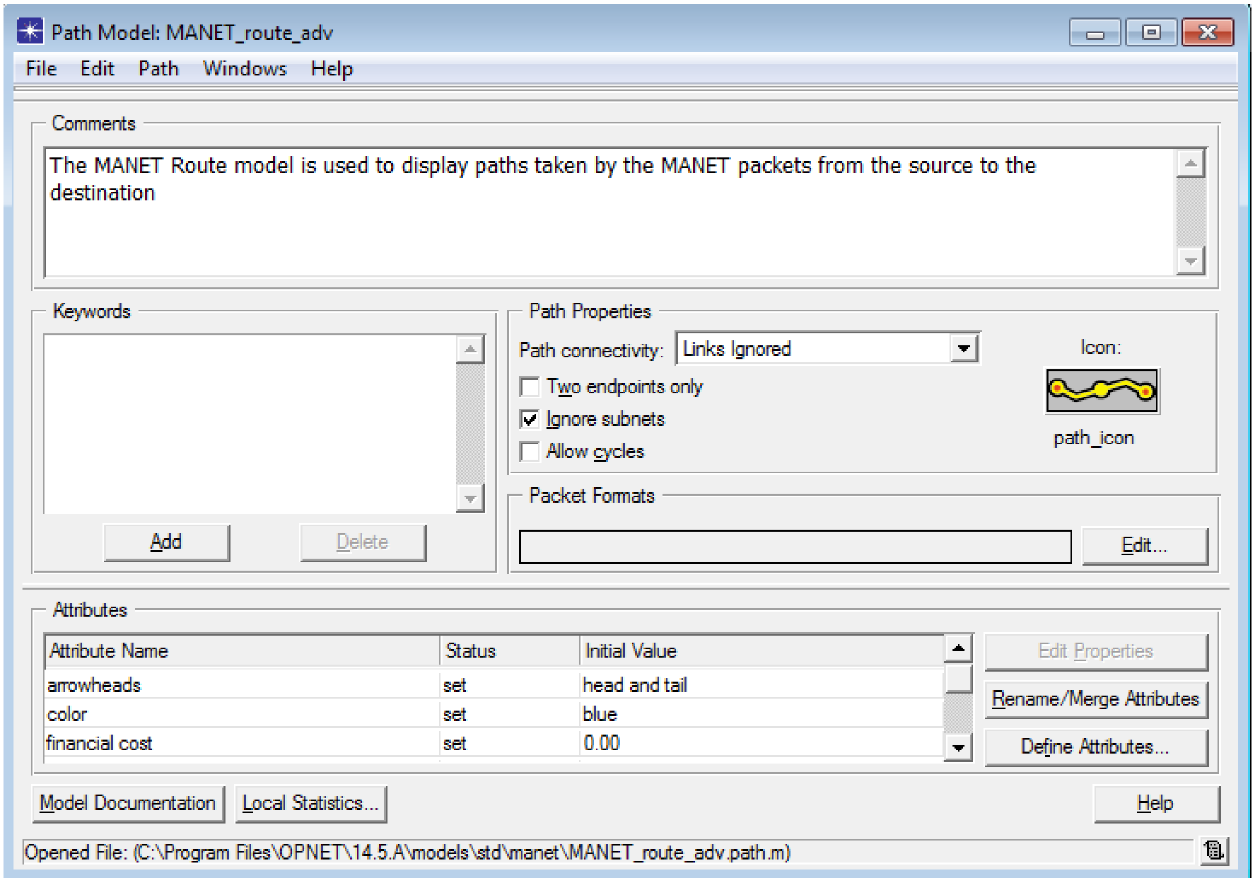

Figure A.6 Path Editor

Probe Editor

Probe editor specifies an interface to collect additional statistics as defined in the network editor. Various types of statistics can be defined using probe editor which are link statistics, local statistics, global statistics and different other animation statistics. The probe editor is shown in the **Error! Reference source not found.**(A.7).

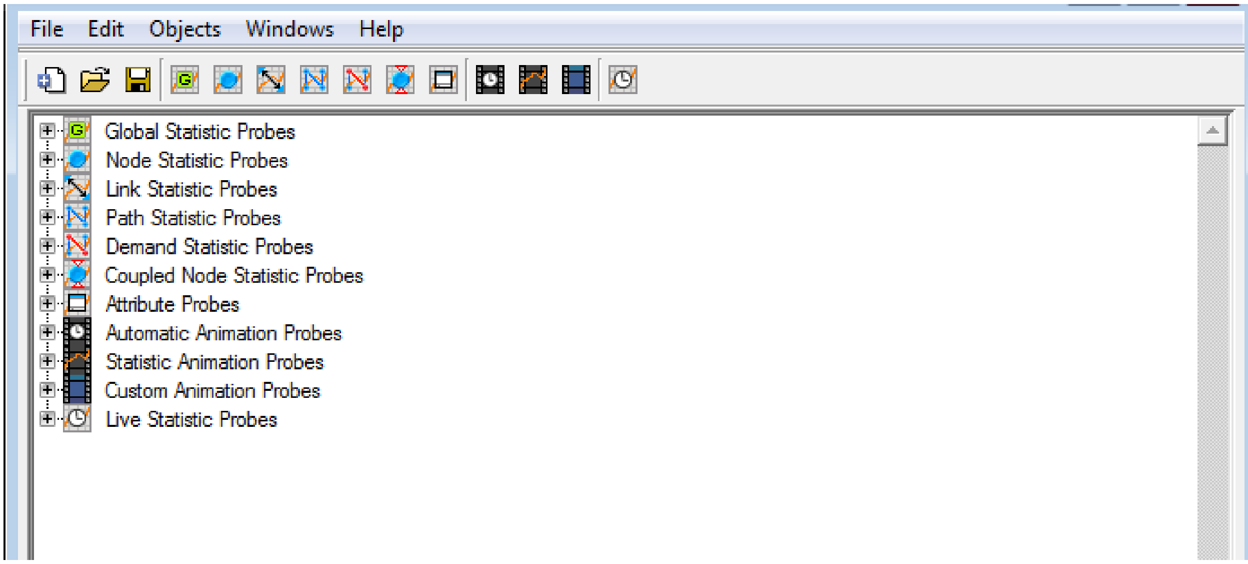

Figure A.7 Probe Editor

Packet Format Editor

A packet can be defined in a packet format editor with specific fields, field names and sizes. OPNET modeler provides a way to define two types of packet formats, one is formatted packets and other is unformatted packets. The packet format editor is shown in the **Error! Reference source not found.** is used to define only the formatted packets. [21], [24], [33], [38-39]

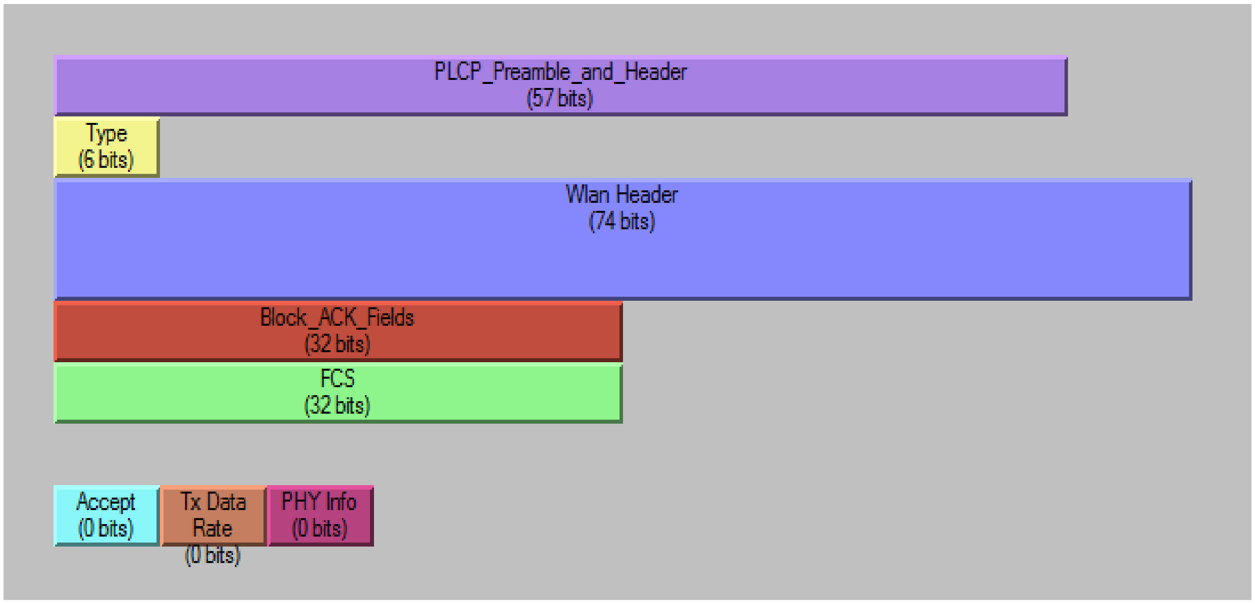

Figure A.7 Packet Editor

Appendix B

Wireless Network Design

OPNET modeler only provides two types of wireless network designs which are Infrastructure mode and Ad-hoc mode. In Infrastructure mode wireless devices in the network all communicate through access point or wireless router. In Ad-hoc mode, wireless devices in the network connect directly to each other. The two types of supported network with a snap shot from OPNET modeler documentation is shown in the figures (B.1-B.2).

Figure B.1 Infrastructure mode

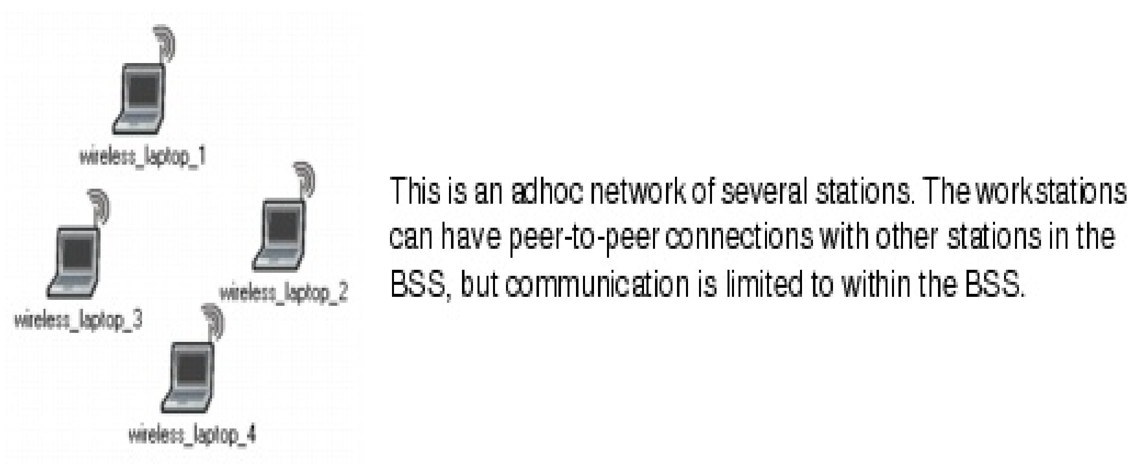

Figure B.2 Ad-hoc mode

OPNET modeler comes with a rich library of WLAN supported devices that can be used to design any type of the mesh network, and all the famous mesh routing protocols are supported in OPNET modeler.

For wireless network deployment, OPNET provides two ways to build a network.

- Deploying through wireless network wizard
- Manual network deployment

Wireless Wizard

The brief overview for deploying Wlan network through wireless wizard is provided here. To access the wizard the following path is required. Topology > deploy a wireless network, the following wizard open as shown in the figure (B.3).

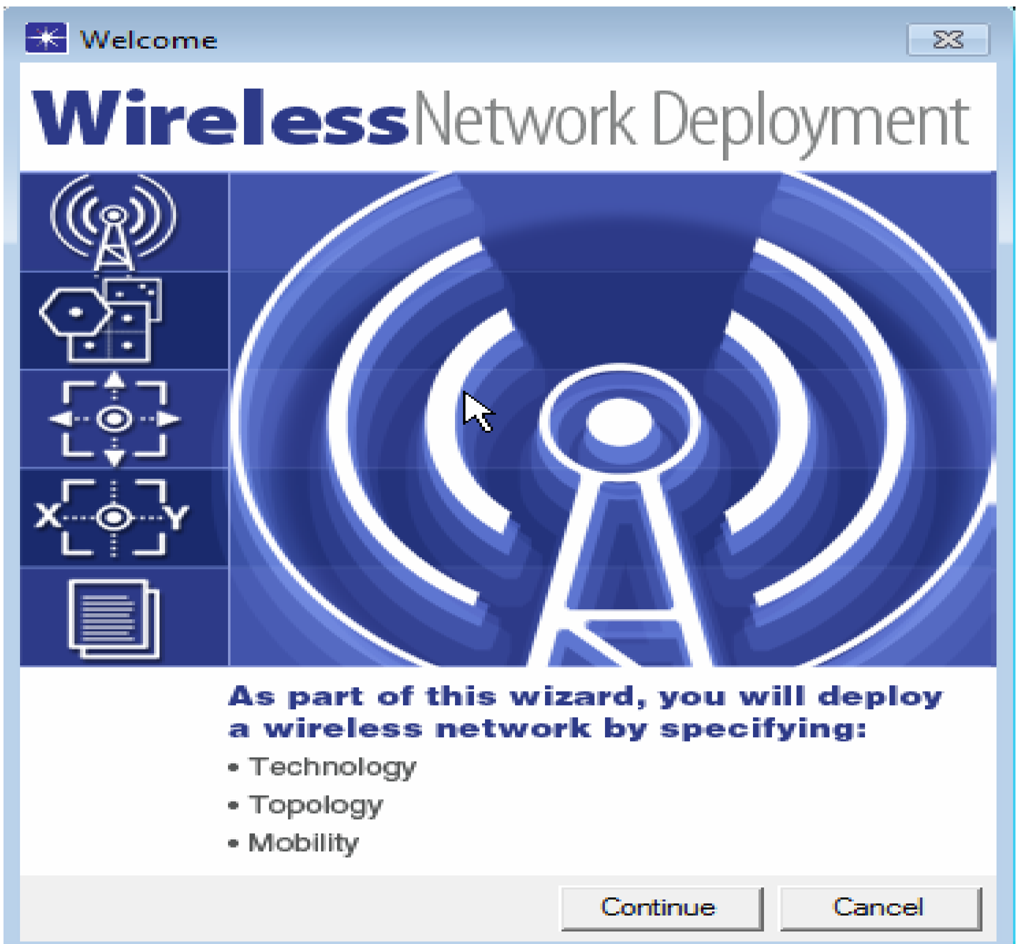

Figure B.3 Wireless Network Deployment Wizard

Choose the type of technology for the wireless network as shown in figure (B.4).

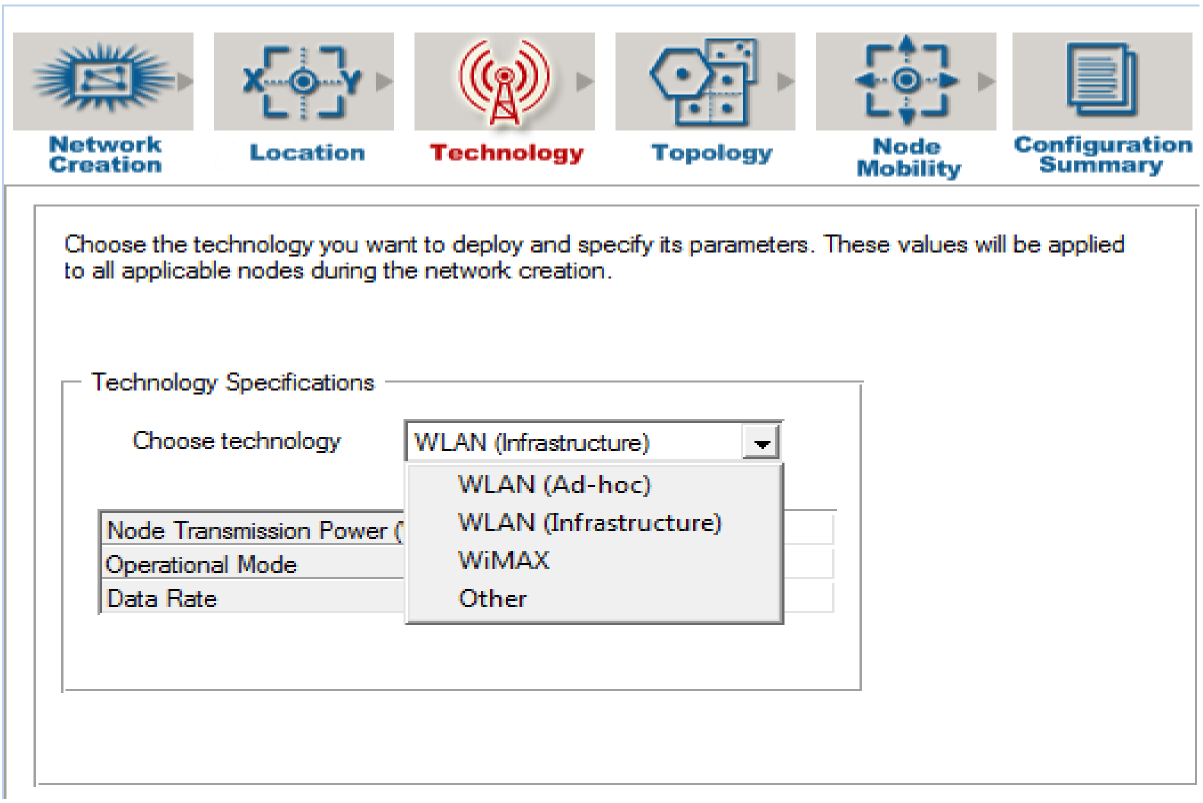

Figure B.4 Wireless Network Types

Transmission power for each node which is corresponding to the area of network, operation mode which can be either b, g and a and the data rate for operation mode can be modify as shown in figure (B.5).

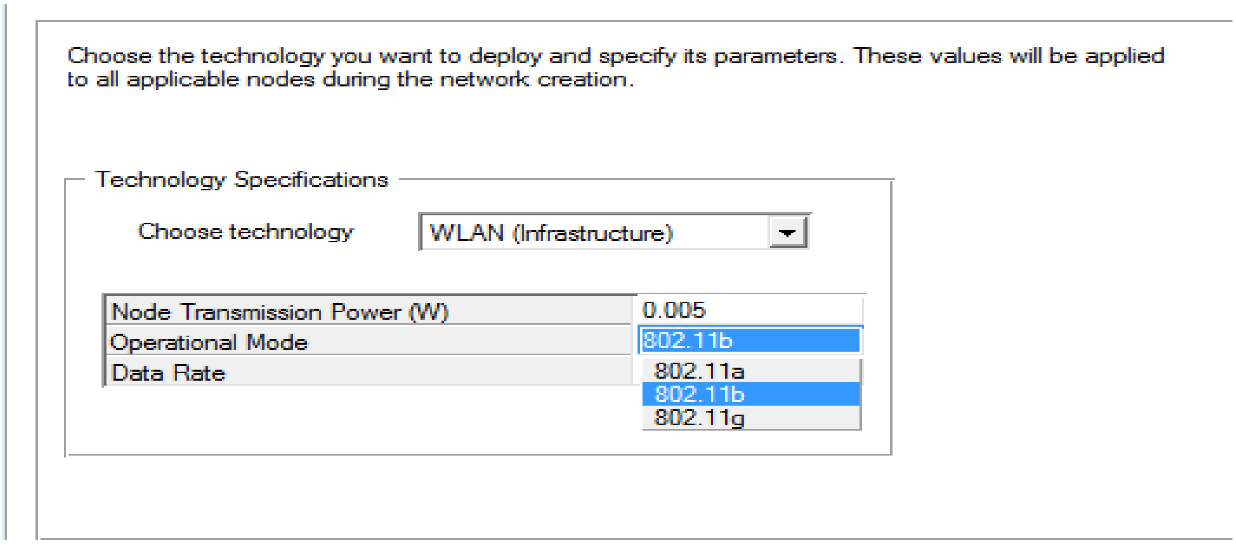

Figure B.5 Wireless Network Technologies

The geographical overlay can either be chosen as cell format or single square network, number of cells and cell or square areas can be selected from topology design as shown in the figure (B.6)

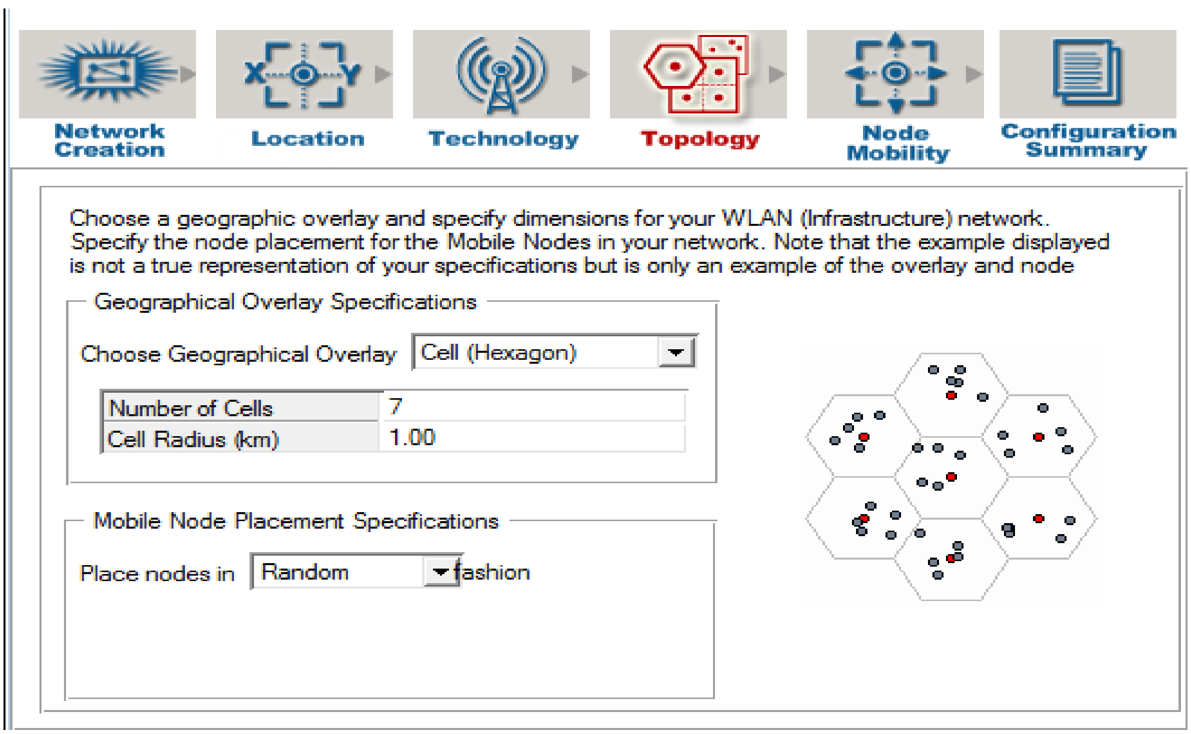

Figure B.6 Wireless Networks Geographical Overlay

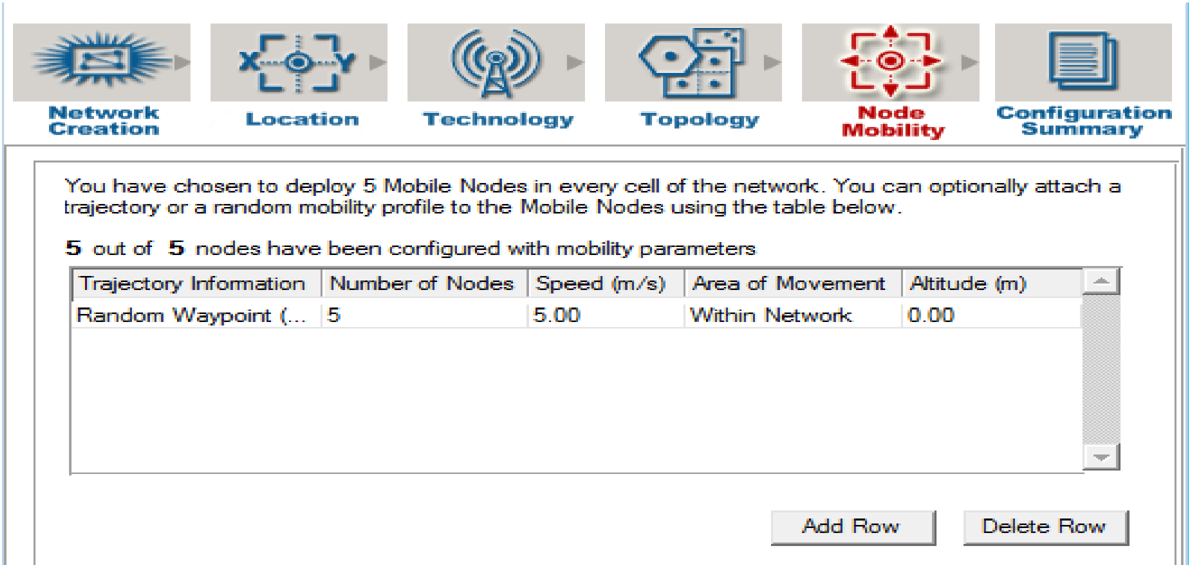

Figure B.7 Wireless Network Node Mobility

Manual Network Deployment

Wireless network can also be deployed manually like wired networks. The procedure for manual deployment is to click on file > new > project > give project and scenario realistic names related to project > create empty scenario > there are different types of region that can be set for the project as shown in the figure (B.8) choose the related network scale and then choose its area > a network window will be formed with all the attributes chose during the wizard. E.g. the figure is showing the campus network with 5x5km area; the scaling is done on the network, each unit of 1 is representing 1km as shown in figure (B.9).

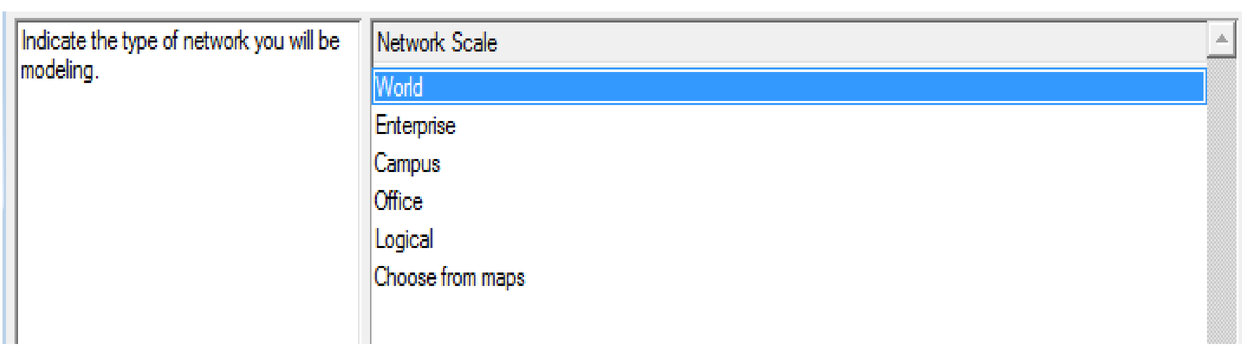

Figure B.8 Wireless Network Region Scale

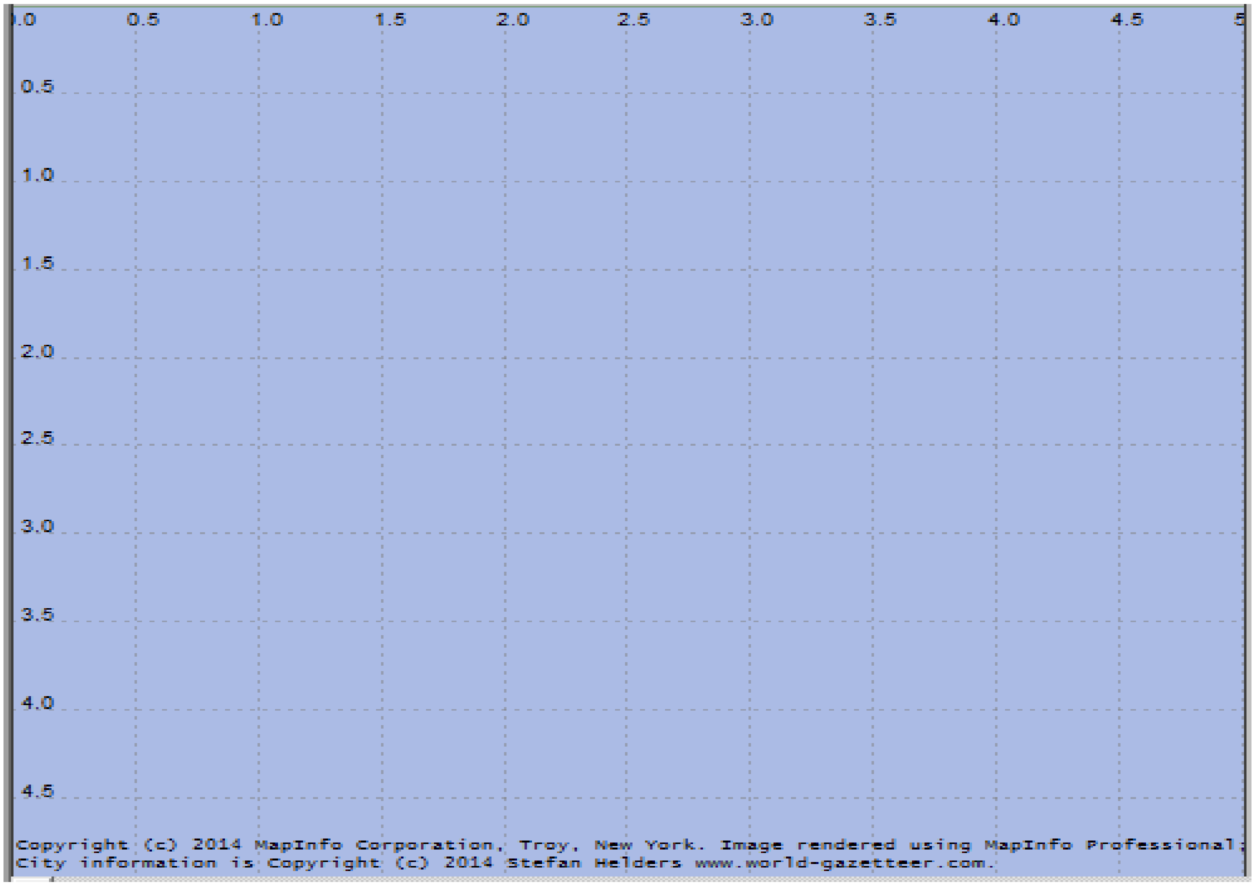

Figure B.9 Manual Wireless Network Deployment

The network architecture that is required to design for this project is shown in the figure (B.10). To design a network like this a manual procedure has been followed because OPNET modeler doesn’t design network like this through wireless wizard.

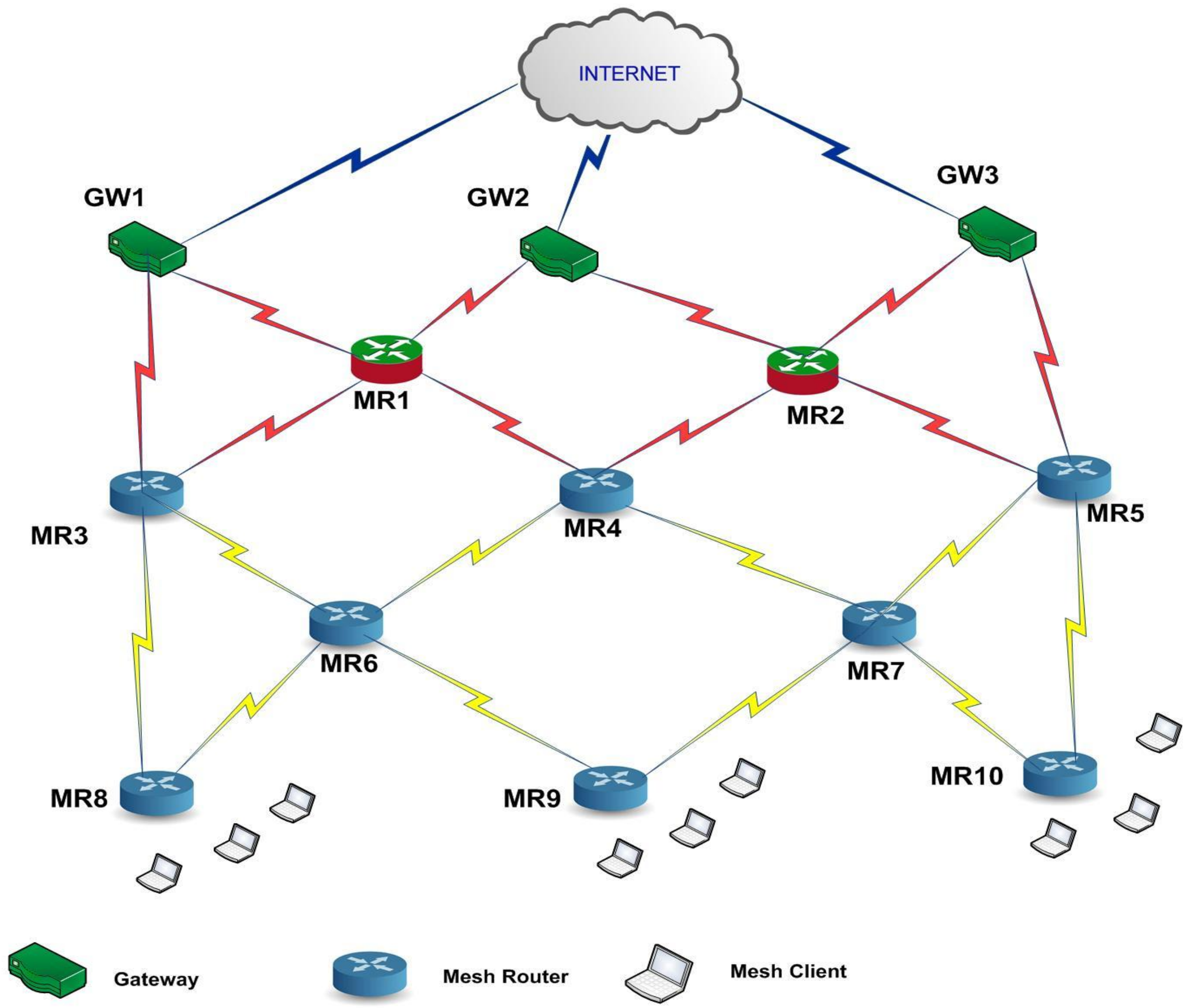

Figure B.10 WMN Architecture

A campus network with area of 5x5km is designed. Wireless routers and clients are accessed from object pallet wireless section, the different types of supported wireless nodes that come with OPNET wireless library is shown in the figure (B.11).

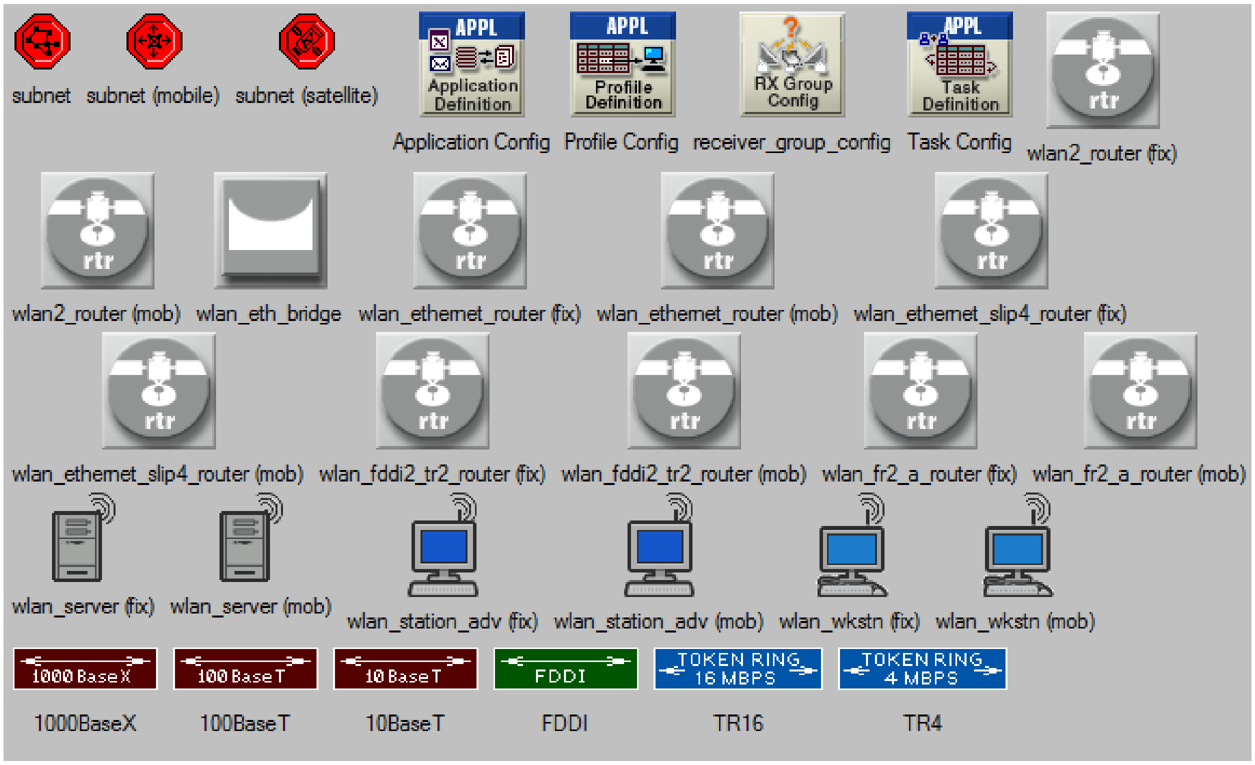

Figure B.11 OPNET Wireless Library

The devices that are used in the campus network similar to the network architecture as shown in the figure above are

Wlan_ethernet_router(fix): It is a single radio wireless lan router with Ethernet interface as well. All the mesh network nodes are of this type.

Wlan2_router(fix): It is a double radio wireless lan router whose one radio is interfaced with the mesh network and another radio works as an access point to connect users to it.

Wlan_wkstn(fix): Wlan client with all supported layers and protocols.

Ethernet4_slip8_gtwy: Internet gateway router for the servers in the network

Ethernet16_switch: It is Ethernet switch connected to the gateway router to provide connectivity to the servers

Ethernet_server: It is an Ethernet server connected to an Ethernet switch in an Internet cloud

Appendix C

Configuration

There are no defaults configurations for the mesh network in OPNET modeler 14.5, therefore some configurations are required to make the network working as a WMN. The mostly used configurations involved in the project are WLAN attributes configuration and routing protocol configurations. A snap shot for the WLAN attributes is shown in the figure (C.1). WLAN parameters such as transmission power, access point functionality, access point id are required to configure in a way that it should provide the services of a mesh router and successful communicate with uplink gateways and access routers.

Attribute	Value
Wireless LAN Parameters (IF0 P0)	(...)
BSS Identifier	1
Access Point Functionality	Disabled
Physical Characteristics	Direct Sequence
Data Rate (bps)	11 Mbps
Channel Settings	Auto Assigned
Transmit Power (W)	0.020
Packet Reception-Power Threshold...	-95
Rts Threshold (bytes)	None
Fragmentation Threshold (bytes)	None
CTS-to-self Option	Enabled
Short Retry Limit	7
Long Retry Limit	4
AP Beacon Interval (secs)	0.02
Max Receive Lifetime (secs)	0.5
Buffer Size (bits)	256000
Roaming Capability	Disabled
Large Packet Processing	Drop
PCF Parameters	Disabled
HCF Parameters	Not Supported

Figure C.1 Wireless Node Attributes

Mesh routing protocol is required to enable on all the mesh routers and configuration of that routing protocol on a specific interface is required. The figure (C.2) shows a list of routing protocol supported by OPNET modeler.

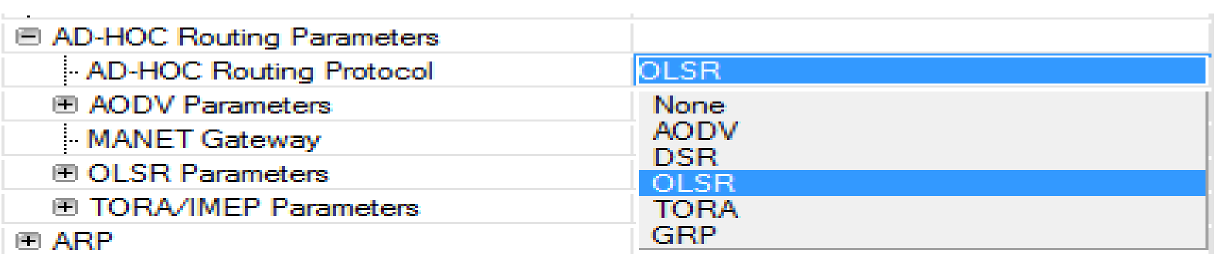

Figure C.2 Ad-hoc Routing Protocols

The figure (C.3) is showing to configure the routing protocol at the interface level

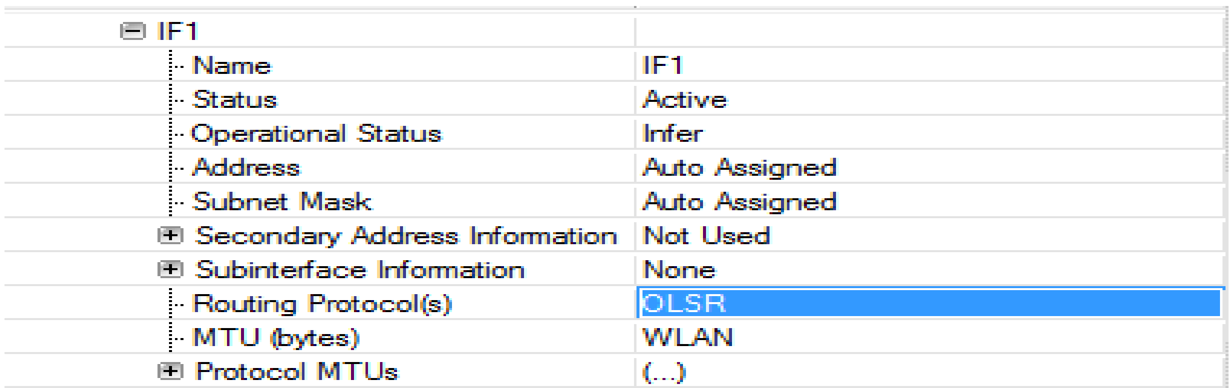

Figure C.3 Wireless Interface Routing Protocols

For proactive routing protocols the gateway information is also required. The static routes are configured on all the mesh routers with next hope of gateway router IP addresses in case of OLSR. As in the case of reactive routing protocol routing table doesn't exist therefore there is no need to configure any static routes on the mesh routers. The static route configuration for the OLSR is shown in the figure (C.4).

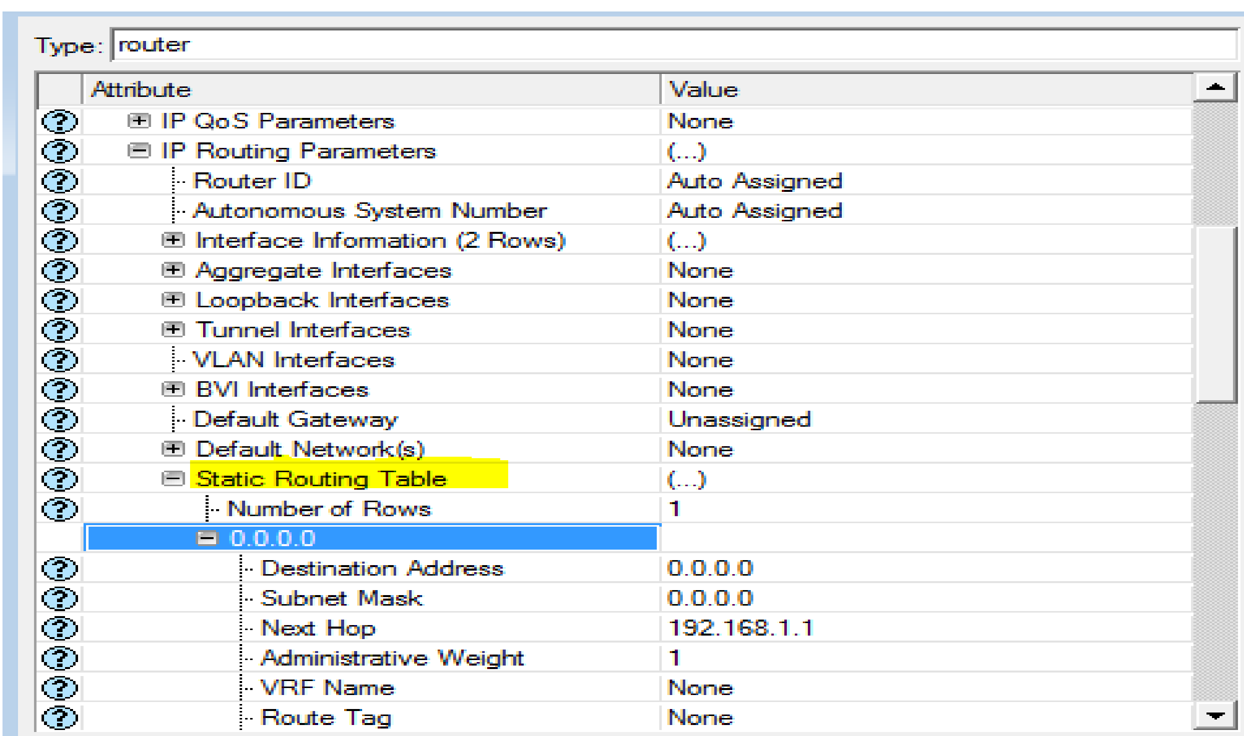

Figure C.4 Static Routing in Wireless Network