PERFORMANCE OPTIMIZATION OF WIRELESS MESH NETWORKS

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

Harish Kongara

Certificate of Approval:

Shiwen Mao
Assistant Professor
Electrical and Computer Engineering

Prathima Agrawal
Samuel Ginn Distinguished Professor
Electrical and Computer Engineering

Sadasiva M.Rao
Professor
Electrical and Computer Engineering

George T. Flowers
Interim Dean, Graduate School

Performance Optimization of Wireless Mesh Networks

Harish Kongara

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
May 9, 2009

Performance Optimization of Wireless Mesh Networks

Harish Kongara

Signature of Author

Date of Graduation

VITA

Harish Kongara son of Venkateswara Swamy Kongara was born on May 23rd, 1985. He received the Bachelor of Technology Degree in Electronics and Communications Engineering from Acharya Nagarjuna University in 2006. He joined Masters Program in Department of Electrical and Computer Engineering at Auburn University in August 2006. His current area of research is focused on Wireless Mesh Networks.

THESIS ABSTRACT

PERFORMANCE OPTIMIZATION OF WIRELESS MESH NETWORKS

Harish Kongara

Master of Science, May 9, 2009
(B.Tech., Acharya Nagarjuna University–India, 2006)

60 Typed Pages

Directed by Prathima Agrawal

Wireless mesh network (WMN) is a communication network consisting of radio nodes organized in a mesh topology. The components of a mesh network are mesh clients, mesh routers for forwarding packets to mesh gateways that connect to the internet. WMNs can be integrated with wired and wireless networks. The wireless networks can be infrastructure based networks such as 802.11 and cellular networks or mobile ad hoc networks. WMNs thus provide a low-cost platform for offering ubiquitous broadband access ranging from local area, metropolitan area and wide area networks. WMNs have interesting properties like self organization and self healing and offer higher reliability. However, there are significant challenges that influence the architecture, design, and deployment of WMNs. Clever algorithms and protocols are needed to realize the true potential of WMNs to address performance, mobility and security issues. WMNs have applications ranging from civilian wireless internet applications to tactical and emergency response applications

In this thesis, we focus on fairness and scalability issues in WMNs and propose solutions to optimize network performance. Two ideas are proposed as a solution to the above problems. First, a differentiated client algorithm is proposed as a potential solution to the scalability problem. In this algorithm the clients are differentiated based on the amount of traffic they generate. It is shown

through NS-2 simulations that there is significant improvement in scalability especially when the network is congested. Second, a gateway classification algorithm (GCA) is proposed to solve the throughput unfairness issue. In general, WMNs are multi-hop networks. The unfairness problem due to the fact that clients (and routers) that are nearer (smaller number of hops from) the mesh gateways may have undue advantage over those that are farther. In this algorithm, the gateways are classified based on their data rate handling capabilities. Extensive NS2 simulations demonstrate the effectiveness of the above two algorithms.

Acknowledgments

I would express my sincere gratitude to my advisor Professor Prathima Agrawal for her guidance and help during my study and research at Auburn. Thanks for leading me into the research area of wireless mesh networks. Without her patience and support, this thesis would not be possible.

I also thank Professors Sadasiva M. Rao and Shiwen Mao for serving on my advisory committee. My thanks also go out to my colleagues in the Wireless Research Laboratory, Yogesh R Kondareddy, Pratap Simha, Srivathsan Soundararajan and Nirmal Andrews for the discussions and valuable suggestions on our research.

I am grateful to my parents for their consistent support and encouragement during my study and thanks to my friends for their kind presence whenever needed.

Style manual or journal used Journal of Approximation Theory (together with the style known as "aums"). Bibliograpy follows van Leunen's *A Handbook for Scholars*.

Computer software used The document preparation package TEX (specifically LATEX) together with the departmental style-file `aums.sty`.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Definition of Wireless Mesh Networks

In Wireless Mesh Networks (WMNs) each node can communicate directly with atleast one node. Each node can also operate as a router and forward packets for other nodes that may not be within the transmission range of their destinations. WMNs are self-organizing with the nodes having the ability to establish an ad-hoc network and maintain the mesh connectivity [1].

1.2 Architecture of Wireless Mesh Networks

Mesh Clients and Mesh Routers are the two types of nodes in Wireless Mesh Networks. The Mesh routers establish the backbone of the Wireless Mesh Networks while the mesh clients act as components of the mesh environment. The mesh routers have functionalities such as gateway/bridge functions allowing the conventional clients with wired or wireless Network Interface Cards (NICs) to connect to the wireless mesh network[1]. Gateway or Bridge functions do not exist in wireless Mesh Clients. Mesh clients have one wireless interface as opposed to Mesh Routers which can have multiple interfaces. Considering all these differences the hardware platform and the software for mesh clients is much simpler compared to mesh routers. The extension of the ad-hoc network is to be able to connect to the Internet. The wireless mesh networks can communicate locally and as well as to the Internet.

The architecture of WMNs is classified in to 3 types: Infrastructure WMNs, Client WMNs, and Hybrid WMNs.

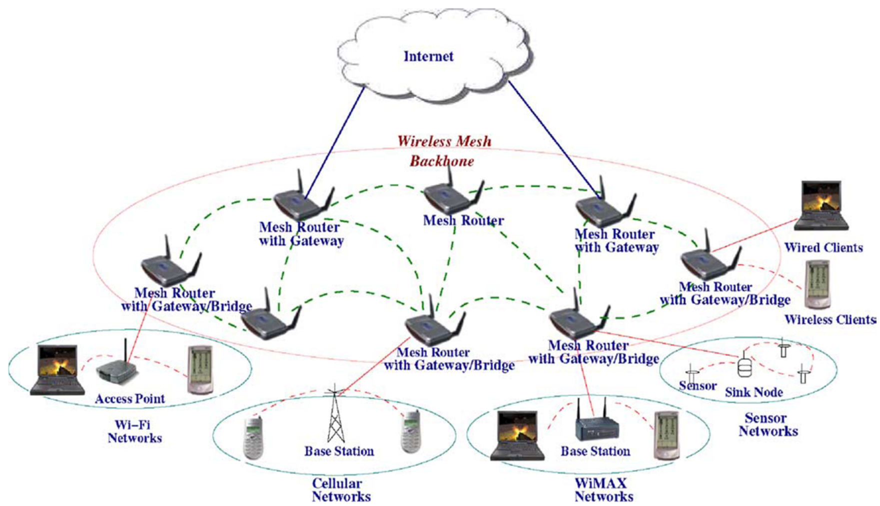

Figure 1.1: Infrastructure Wireless Mesh Network [1]

1.2.1 Infrastructure based Wireless Mesh Networks

In Infrastructure Wireless Mesh Networks the mesh routers form mesh infrastructure among themselves and provides architecture for conventional clients and provides services through gateway/bridge functionalities. This type of architecture is less common in real world systems. The architecture is shown in Figure 1.1 [1].

1.2.2 Client Wireless Mesh Networks

Client Wireless Mesh Networking is a synonym for ad-hoc networking. In this architecture there are no mesh routers and clients form the network and communicate among themselves. The clients can communicate among them locally. But they cannot connect to outside world other than their own clients. This kind of architecture is more common in military applications. The architecture is shown in Figure 1.2 [1].

1.2.3 Hybrid Wireless Mesh Networks

Hybrid Wireless Mesh Network architecture is a combination of Infrastructure and Client Wireless Mesh Network architecture. The clients can access the network through mesh routers or through

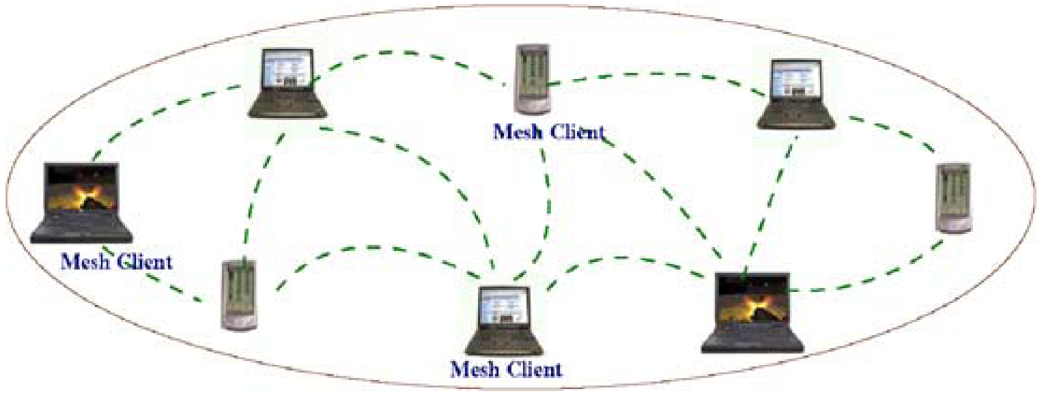

Figure 1.2: Client Wireless Mesh Network [1]

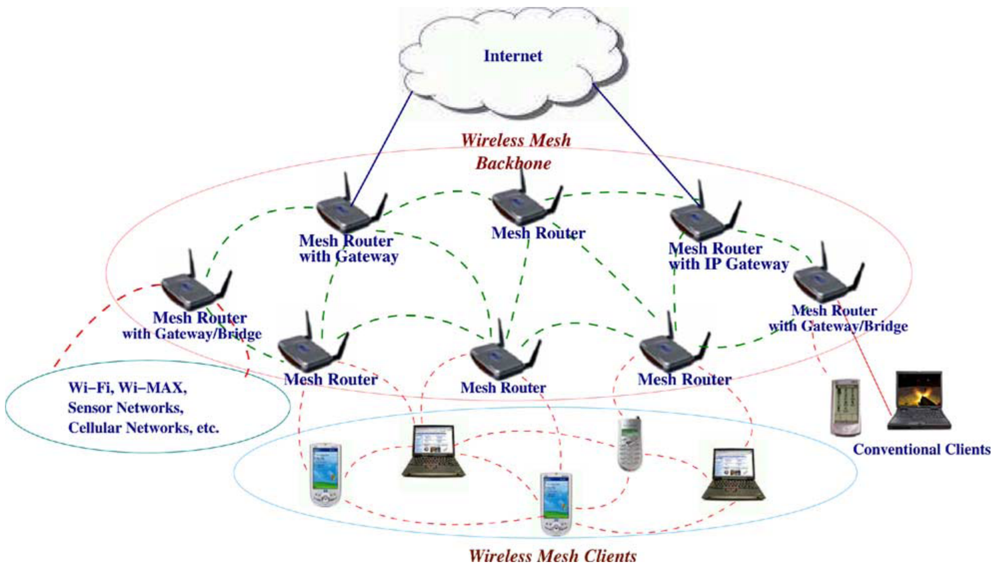

Figure 1.3: Hybrid Wireless Mesh Network [1]

other clients. This is the most common type of architecture in real world systems. The architecture is shown in Figure 1.3[1].

1.3 Characteristics of Wireless Mesh Networks

The characteristics of WMNs are explained as follows:

1.3.1 Beyond ad-hoc Networking

The Wireless Mesh Networks support ad-hoc network environment with in the mesh clients allowing them to communicate. One of the extension of the wireless mesh network is to able to communicate to the internet. The wireless mesh networks with mesh routers connected to the gateway makes it possible allowing the Mesh and Conventional clients to connect to the internet [1].

1.3.2 Different types of Network Access

In WMNs, the network access is of many kinds such as peer to peer, ad-hoc, and also the Ethernet cards supported by the mesh routers [1]. The clients communicate among themselves to reach to a mesh router. In an ad-hoc environment there is no background architecture and all clients communicate among themselves. Wireless Mesh Routers can be added to the wireless mesh network environment based on the number of users in the network environment.

1.3.3 Power-Consumption

Power requirements of the wireless mesh networks is differentiated in to two types for mesh routers the power requirement is more whereas for the mesh clients the power requirement is less and mesh nodes can use solar energy or hydro power.

1.3.4 Multiple Radios

Mesh routers have multiple radios which separates two main types of traffic such as user traffic and routing traffic which are handled by different radios. This improves the capacity of the network [1].

1.3.5 Robustness

We expect the networks to be robust to work in any condition even though some point of the network fails. WMNS have higher network robustness due to the availability of many mesh routers and different paths to access the network [1].

1.3.6 Scalability

In Wireless Mesh Networks hundreds of nodes can be added at anytime to the network and the network is completely scalable.

1.4 Differences between Wireless Mesh Networks and ad-hoc Networks

A stand alone temporary network of wireless mobile hosts over a network in which the hosts are normally connected is called ad hoc network (Johnson and Maltz). In Wireless Mesh networks, routing and configuration functionalities are performed by mesh routers where as end user devices are used in ad-hoc networking to perform these functions. So, Mesh routers in Wireless Mesh Networks result in lower power consumption and higher throughput.ad-hoc networks use single channel for network traffic, routing and traffic configuration, this leads to reduction in overall performance and it has an inherent problem to configuration and deployment for a moving user. Usage of Multiple radios in Wireless Mesh Networks support mobile clients and also enhances network performance.

1.5 Wireless Mesh Networks Applications

1.5.1 Home Based Broadband Networking

Now a days IEEE 802.11 WLANs are being used for home based broadband networking. Even though these networks allow wireless data access and transfer capabilities, these networks have a

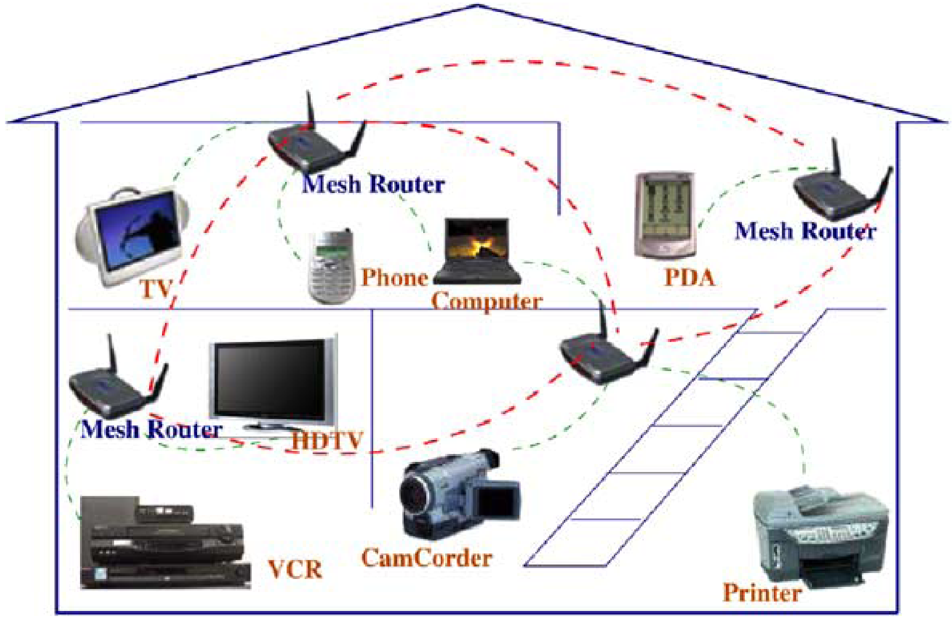

Figure 1.4: WMNs for Home Networking [1]

disadvantage in terms of access points, which can lead to dead zones (no service coverage). This problem can be avoided by installing multiple access points, but this could be expensive and cumbersome due to Ethernet wiring from access point to backhaul network modem (hub). Communication between two user nodes in their transmission range under two different access points have to go all the way back to the access hub, in multiple access point network. Mesh networking provides a perfect home networking architecture. The architecture is shown in Figure 1.4 [1].

1.5.2 Enterprise and Community networking

A single office in a building or multiple rooms in the same building which are connected in a network, represents enterprise networking. Currently data communication in these environments are provided by IEEE 802.11. As discussed previously (Home based broad band networking) this is also suffered by extensive usage of Ethernet cables. Even though usage of multiple modems can increase local network capacity, but the robustness of these networks is questionable in the case of network failure, it prohibits end user from data access or transfer. Community networks are based on cable or DSL internet connection. Wireless routers, which are connected to internet modem are being used by the end users for the internet access. This network is effective with for an individual user, but this suffers from reduced network utilization, as all the information transfer should go through internet with in a neighborhood. Wireless mesh networks (WMNs) can be very effective in these scenarios, due to its flexible connections between offices and neighborhoods. Availability of multiple paths to access internet despite of link failures can improve the network robustness.

1.5.3 Other Applications of Wireless Mesh Networks

Major advantages such as scalability and internal communication (with in the mesh clients) have made Wireless Mesh Networks ideal for metropolitan area networking (MAN), transportation systems, building automation, Health and Medical Systems. Mesh networks can also be implemented in moving train, so that the passengers in a train can communicate among themselves and access the internet through a gateway in the vehicle. WMNs can be useful tool in the surveillance and health care institutions (patients data can be stored and accessed from different locations, so this helps doctors in faster diagnosis and better services). The architecture for Transportation Systems is shown in Figure 1.5. [1].

The Wireless Mesh Networks can also be used in various Electrical and power companies to control the machines. In the present world the various systems in the industry are controlled using the wired network. But the wired network is difficult to deploy and expensive, recently Wi-Fi networks are employed but not successful due to the backend ethernet connection which results in high cost of deployment. In these cases the wireless mesh routers can be deployed and the information from them can be used to control the electrical machines and motors [1].

In Health and Medical systems, the data of the patient is need to processed in different rooms in an hospital. Present day hospitals used wired connections to transmit data from one room to another which prohibits access of the data to all rooms due to the cumbersomeness of wired networks [1]. In

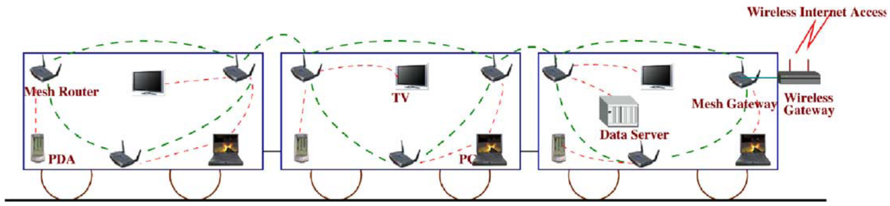

Figure 1.5: Wireless Mesh Network for Transportation Systems [1]

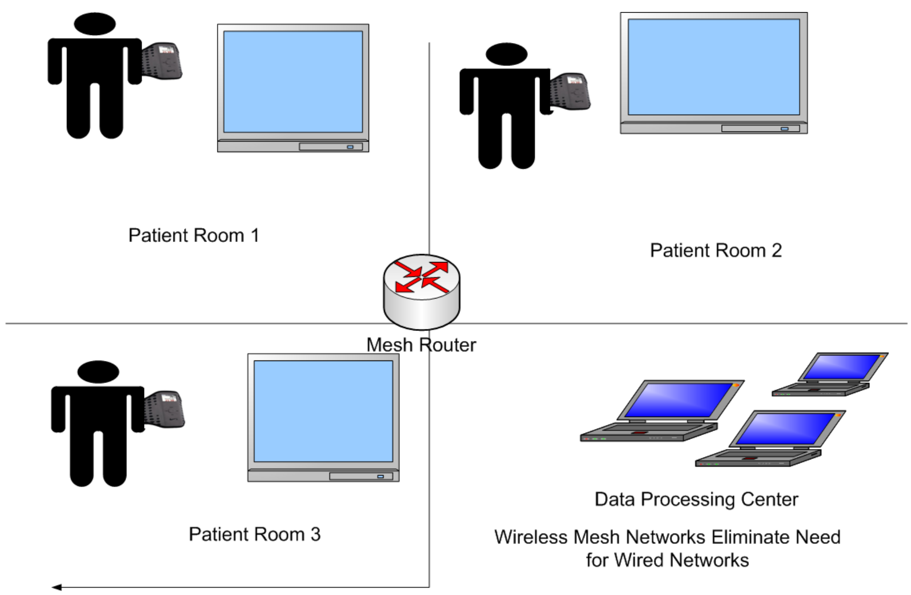

Figure 1.6: Wireless Mesh Network in Hospitals eliminate the need for Wired Network

wireless mesh networks as shown in the Figure 1.6 the data from different rooms can be transmitted to the data processing center using mesh routers also the data can be transmitted globally bu using the gateway connection to the internet.

Wireless Mesh Networks can also be used in security systems where the data can be transmitted through the mesh routers. In wired networks the entire security area need to be covered using the wired networks. But in wireless mesh networks when an emergency occurs in a new place simply installation of one mesh router transfers the data through the entire emergency environment [1]. This scenario has a vital importance during emergency disasters where the firefighters and the police can deploy one wireless mesh router to transmit the data from an unknown emergency area without the need of installing additional wired networks[1].

The rest of the document is organized as follows. Chapter 2 introduces the scalability problem of wireless mesh networks and analyzes the variation of performance of wireless mesh networks with respect to data rate of clients, error rate and gateway placement.Finally a solution to the scalability problem is provided at the end of the chapter.Chapter 3 introduces the unfairness issue in a multihop wireless mesh network environment. It deals with the different traffic models that demonstrate unfairnes among different hops.The proposed GCA is presented in this chapter which provides a solution for the unfairness issue in wireless mesh networks. Section 4 concludes this document.

CHAPTER 2

STUDY OF SCALABILITY IN WIRELESS MESH NETWORKS USING NS-2 SIMULATIONS

2.1 Definition of Scalability in Wireless Mesh Networks

In a telecommunication network environment it is desired that more and more number of nodes are added to the network anytime without the degradation of the network performance. One of the architecture advantages of wireless mesh networks is that the network can be scalable to any number of nodes. But the existing protocols in wireless networks are not suited for the network to be completely scalable. SO new protocols are to be designed or existing protocols must be modified to support the scalability of wireless mesh networks.

In WMNs, it is desired that more nodes can be added when necessary. However, with the existing 802.11 protocols as number of nodes increase, interference increases thereby decreasing the throughput. It is shown that the asymptotic capacity for each node decreases with the number of nodes as O(1/n) where n is the total number of nodes in the network [2]. The network performance depends on a number of factors, the network performance varies with the error rate, data rate of clients, gateway placement, propagating conditions and different carrier sensing thresholds. The experimental setup is shown in the Figure 2.1. The experimental setup consists of mesh routers, clients and gateways in a multi hop network environment.

The scalability issue is shown in Figure 2.2. In Figure 2.2. each individual client is analyzed for the throughput variation as more and more number of mobile clients are added to the network. As seen from the Figure 2.2. as more and more number of nodes are added to the network the throughput of the individual clients is reduced. This results in a decrease in the average throughput

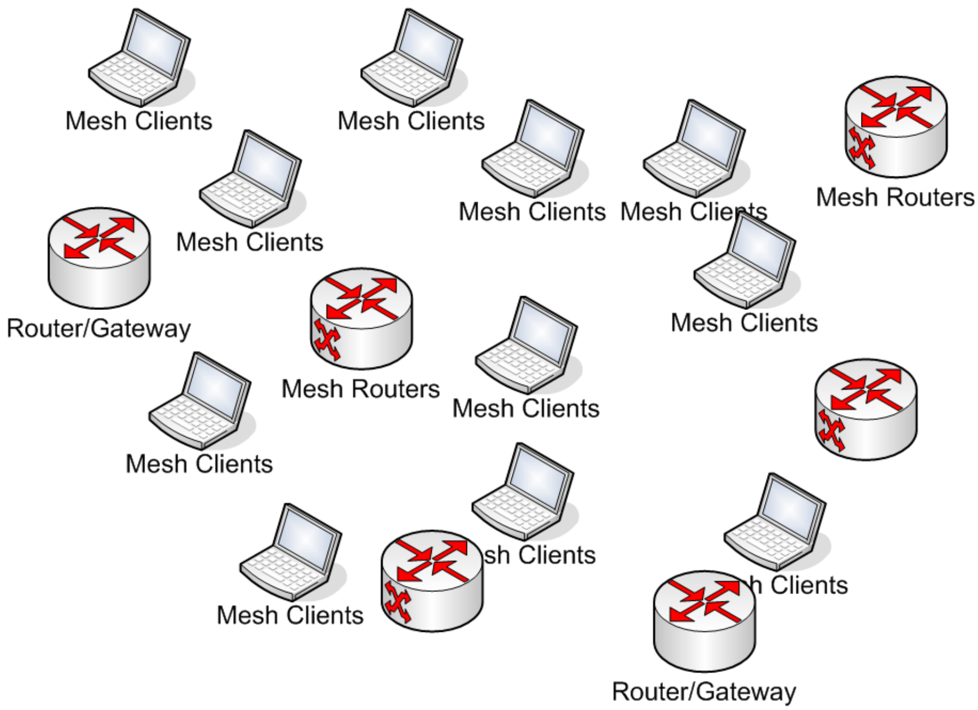

Figure 2.1: Experimental setup demonstrating the network performance

of the overall network. As we can see for some the clients in the Figure 2.2., the client 6 the throughput is dropped from 50 KBPS to 4KBPS. The results show that the existing network protocols of 802.11 are not suited for the scalability of wireless mesh networks.

2.1.1 Average Network Throughput

In this section a new definition is introduced for average network throughput. The average network throughput is defined as the throughput per client. If the aggregate throughput of all the clients in a network is 'x' and the number of clients in the network is 'n' then the average network throughput is given as 'x/n'.

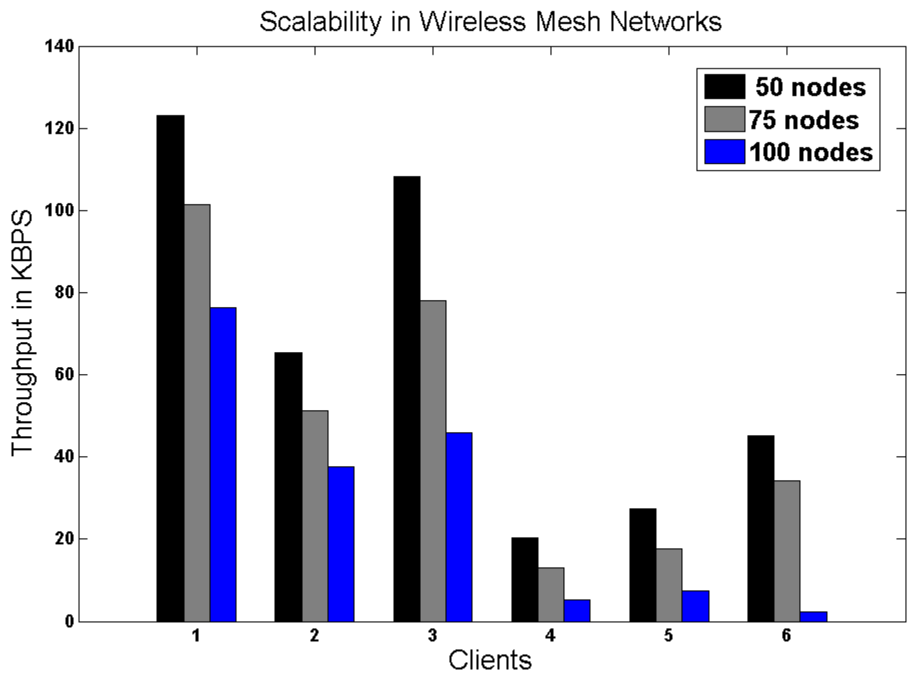

Figure 2.2: Scalability in Wireless Mesh Networks

2.1.2 Characteristics of Average Network Throughput

There are a few characteristics for average network throughput such as it decreases with increase in number of clients in the network, it depends on the data rate of the clients, error rate and gateway placement.

The Lagrange polynomial [64] can be used to estimate the variation of the network performance based on the number of clients. The Lagrange polynomial is an interpolating polynomial of the nth order which passes through n+1 points and is given by

L(x)=$\sum_{j=0}^{n} y_j(x) \times l_j(x)$ [64]

The Lagrange polynomial can be used to find the variation of overall network throughput. Here we derive the Lagrange polynomial for 2 different cases. Let us derive the Lagrange polynomial for 2 different cases and observe the differences

Case 1:

In the case 1, let us consider a variation of mesh clients from 10 to 20. By Experimental results, we have the network average throughput for 10 clients as 52.835Kbps. For 15 mesh clients we have the network average throughput as 37.24Kbps, for 20 Mesh clients the network average throughput is given as 22.03Kbps

$x_0 = 10.0$ $f(x_0) = 52.835$ $x_1 = 15.0$ $f(x_0) = 37.24$ $x_2 = 20.0$ $f(x_0) = 22.03$

The basis polynomials are

$l_0(x) = 1.0567x^2 - 36.9845x + 317.01$

$l_1(x) = -1.4896x^2 + 44.688x - 297.92$

$l_2(x) = 0.4406x^2 - 11.015x + 66.09$

The final Lagrange polynomial is given as

$L(x) = 0.0077x^2 - 3.3115x + 85.18$

If we substitute x=10 in the above equation we get the network average throughput as 52.815Kbps which is almost same as the experimental results. If we substitute x=20 we have network average throughput as 22.03Kbps which is same as the experimental results. From the Lagrange equation we can find the network average through for any number of mesh clients in between 10 and 20 in this topology. Let us verify the next case where the mesh clients are varied from 10 to 70.

Case 2: In this case if we consider 'r' mesh routers , 'g' gateways and the number of mesh clients is varied from 10 to 70. The experimental results give us the network average throughput as 60.283Kbps when the number of mesh clients are 10, When the number of mesh clients are improved to 45 the network average throughput is given as 37.802Kbps, when the number of mesh clients are improved to 70 the average network throughput is given as 17.32Kbps. Based on these three results we can derive a polynomial which will allow us to estimate the average network throughput for clients numbering between 10 and 70

$x_0 = 10.0$ $f(x_0) = 60.28$ $x_1 = 45.0$ $f(x_0) = 37.802$ $x_2 = 70.0$ $f(x_0) = 17.32$

The basis polynomials are

$l_0(x) = 0.028x^2 - 3.3x + 90.42$

$l_1(x) = -0.0604x^2 + 4.838x - 30.2416$

$l_2(x) = 0.0115x^2 - 0.635x + 5.196$

The final Lagrange polynomial is given as

$L(x) = -0.0209x^2 + 0.903x + 65.3744$

where x is the number of mesh clients and x varies in between 10 and 70. With the help of the above equation we can find the average throughput of the network for any number of clients between 10 and 70 for the above topology.

If we substitute x=10 in this Lagrange equation we get average network throughput as 72.33Kbps. The average network throughput for 50 mesh clients is given by substituting 'x'=50 in the above equation, we get the average network throughput as 58.27Kbps.

As seen from the Lagrange equation in this case the average network throughput derived from Lagrange equation just gives an approximate value but not the exact value. This is due to the fact involved as there are many number of mesh clients in the environment and we derived the equation only with 3 experimental results. For better results the equation should be derived using more number of experimental results. So we can say that as more number of mesh clients are involved in the network we should use more number of experimental results to get accurate approximations.

2.2 Variation of Network Performance

In moving forward with the wireless mesh network variation with respect to different parameters we would like to introduce the two most familiar problems of wireless networking the hidden terminal and exposed terminal problems

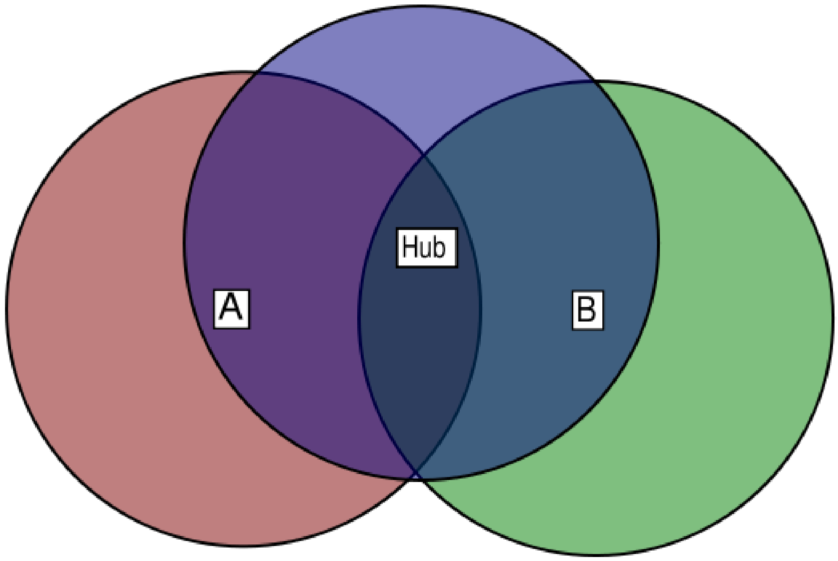

Figure 2.3: Hidden Terminal Problem [62]

2.2.1 Hidden Terminal Problem

The hidden terminal problem is explained by the Figure 2.3 [62]. below the nodes A and B can communicate to the hub, but they are hidden from eachother and as a result of this both A and B transmit packets to the hub and a collision occurs at the hub resulting the loss of packets from both A and B nodes.

The IEEE 802.11 uses the RTS/CTS which are request to send/ clear to send signals as a solution to the hidden terminal problem. The sending node sends a request to send signal to the destination node and the destination node send a clear to send(CTS) signal in response. Any other node which hears the RTS/CTS should not transmit any packets during the interval of time mentioned in the RTS/CTS. This partly solves the hidden terminal problem but they are some disadvantages with this approach in a network environment such as wireless mesh networks in which there are very large amount of nodes.

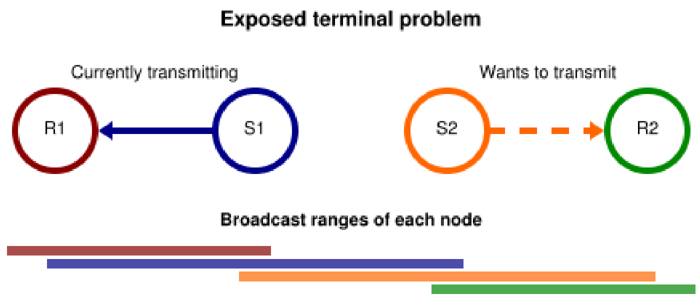

Figure 2.4: Exposed terminal problem [63]

2.2.2 Exposed Terminal Problem

The exposed terminal problem is explained by referring to the Figure 2.4 [63]. below. When the node S1 is sending data to R1, the node S2 cannot send data to R2. The hidden and exposed terminal problems play an important part in determining the performance of wireless networks.

2.2.3 TCP Vs UDP

TCP and UDP are the transport layer protocols used for the transmission of the packets through the internet. TCP is used for connection-oriented transmissions and UDP is used for connectionless transmissions. In connection-oriented transmissions a connection is established between the end users before transmission of any data, where as in the connectionless transmissions there is no connection established between the end users. In general connection-oriented transmissions are called reliable transmissions. TCP is a reliable protocol compared to the UDP.

In our simulation experiments TCP is used to transfer packets from the clients to the internet. TCP has additional advantages compared to UDP such as error correction and flow control. Flow control determines the flow of the packets from source to destination based on the window size of the destination node. The TCP initiates a connection through threeway hand shake. When a transmission is through TCP it is ensured that all the packets are received in the correct order to the destination.

In modern days, Wired Networks the error rate is mainly negligible. TCP assumes that the packet loss is due to the congestion in wired networks. But in the wireless networks the error rates are not negligible, there are lot of other factors in wireless environment resulting in the packet loss, but TCP which is designed for wired networks basically initiates the congestion algorithms in wireless networks when there are loss of packets. Because of the congestion algorithms the throughput of the wireless networks is greatly reduced as a result of decrease in the window size.

2.2.4 Error Rate vs Network Performance

It is obvious that with increase in the error rate the network performance decreases. Error rate depends on various factors and it determines the number of successful packets in total number of packets transmitted. The packet error rate depends on the bit error rate and the collision time. In the simulation environment used the error rate is introduced so as to calculate the effect of error rate on network performance. In the NS2 simulation environment the error model uses a flag on the packet to introduce errors in the transmission. There is a error rate factor in the simulation environment which allows us to change the error rate for different simulations. In our experiment we simulated the network for 4 different error rates randomly. For a multi-hop wireless mesh environment, the hop performance variation with respect to the error rate is shown in Figure 2.5. As depicted from the figure the error rate for the network affects the 3rd hop clients. As the error rate increases the loss of packets increases and the retransmissions are increased. Due to this, the packets from the farther hops experience more hidden terminal and exponential back-off problems, resulting in a severe loss of throughput. The results show that the 3rd hop performance is almost zero with an increase in the error rate. The Experimental Results are depicted in Figure 2.5.

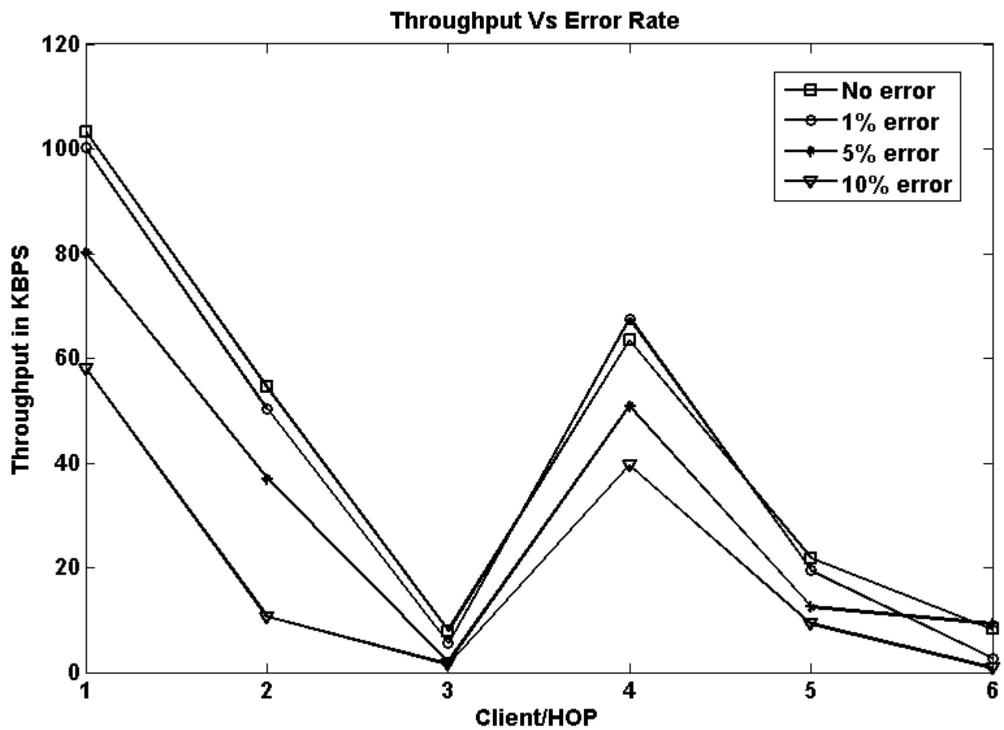

Figure 2.5: Error Rate vs Network Performance

2.2.5 Data Rate of Clients vs Network Performance

Different mesh clients transmit at a different data rate. Based on the applications accessed by the clients the data rate required for the successful running of application varies. So the clients which are accessing different applications have different data rates. The overall network performance is affected by the data rate of the individual clients. The variation of the throughput of the clients with respect to the data rate is observed. The simulation is performed using 100 mesh clients. In addition, the percentage of high data rate clients is varied in different simulation scenarios. Examples of some of the applications requiring high data rate are video streaming and some examples of low data rate applications are text messaging. In the experimental setup the percentage of high date rate clients is taken as the measure of variation, the percentage of high data rate clients is varied in three different scenarios and the results are plotted comparing each other. The results are shown in Figure 2.6. In the Figure 2.6. equally distributed clients refers that half of the clients are using low data rate applications and another half of the clients are using high data rate applications. In the second and third scenario the high data rate clients is improved to 75 percent and 85 percent respectively. The high data rate clients transmit data at a faster rate and hence the interference increases and the throughput decreases, which are depicted in the experimental results.

2.2.6 Gateway Placement vs Network Performance

Also the hop performance is affected by the placement of the gateways. The number of gateways and the placement of the gateways can be changed in an environment. By experimenting with different placement of the gateways, the maximum performance is determined. In an 'n' mesh/ conventional client environment, there is a need for n/2 mesh routers and n/6 gateways and the placement of the gateways is in such a way that the gateways always hold the center of the mesh routers. The performance of the gateway arrangement compared to the distributed gateway is compared. The results are shown in Figure 2.7. Comparing the results of the gateway placement, it

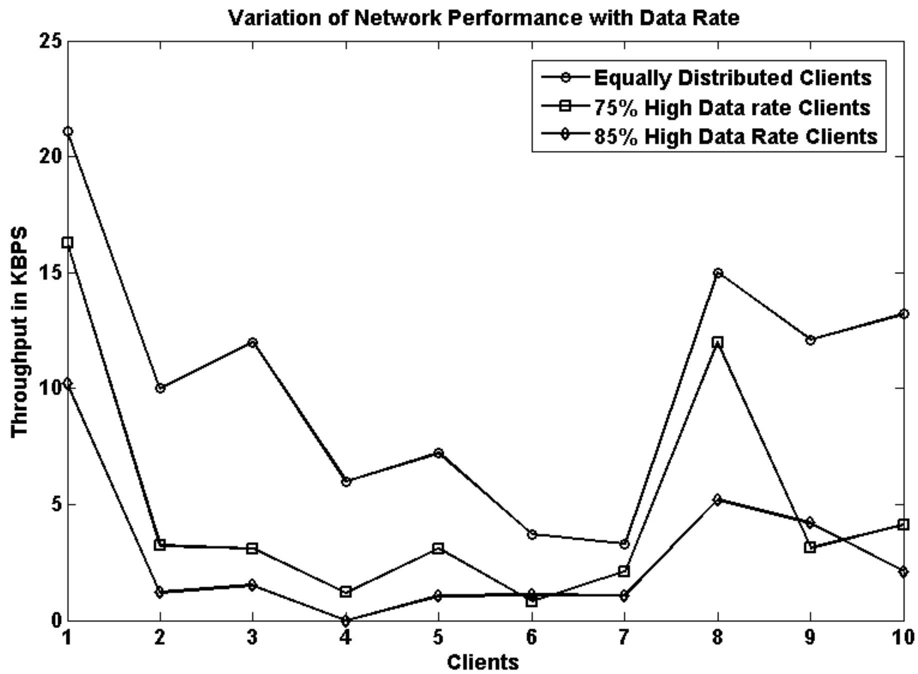

Figure 2.6: Data Rate vs Network Performance

shows that properly choosing the gateways will affect the performance of the overall throughput of the network. The Results are shown in Figure 2.7.

2.2.7 Data Rate vs Number of Clients vs Network Performance

As the number of clients increases the interference increases and also as the data rate of the clients increases the interference increases. In this case both are taken in to consideration.

The threshold throughput here is defined as the minimum average network throughput so that each client can access the internet. If the Average network throughput is below the threshold one or more of the network clients cannot access the internet. From the simulation results shown in the above Figure 2.8. as the data rate of the clients is increased the threshold is reached early compared to less data rate clients. In the above example for the datarate 1 the threshold is reached at 55 clients that is all the 55 clients are able to access the internet. In the datarate 2 the threshold is reached for

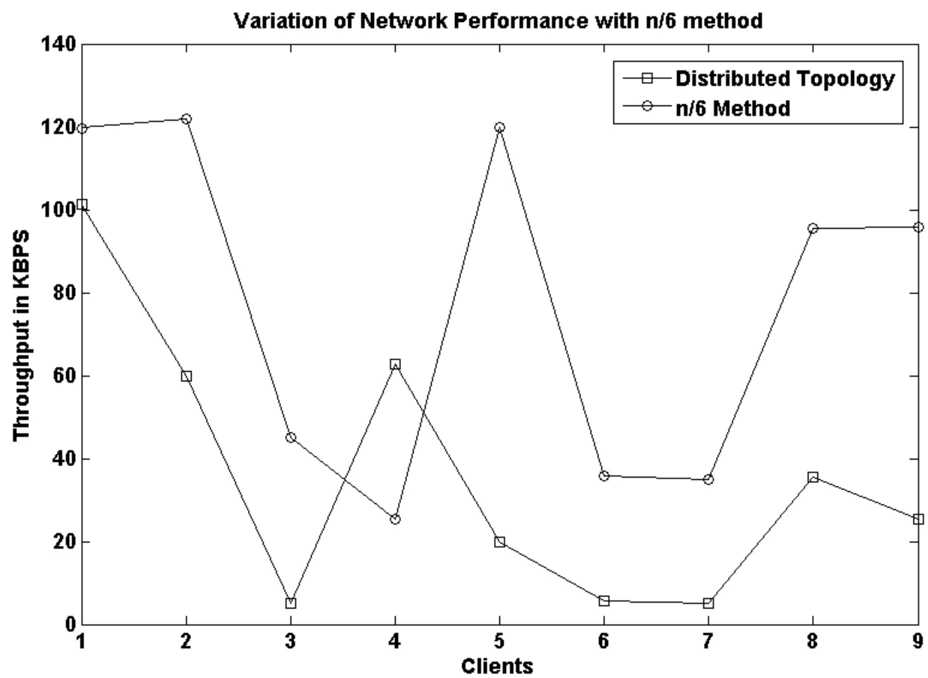

Figure 2.7: Gateway Placement vs Network Performance

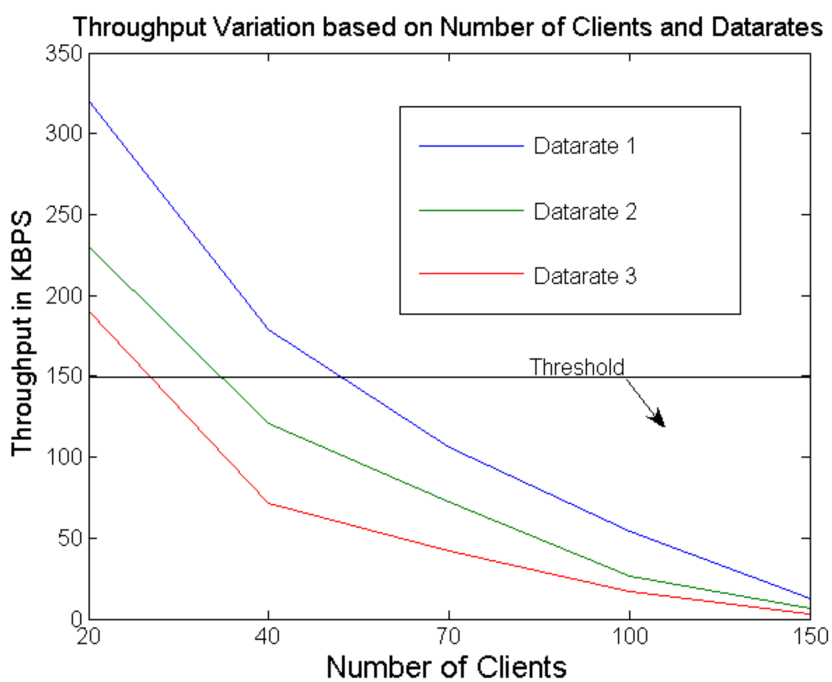

Figure 2.8: Data Rate vs Number of Clients vs Network Performance

less number of clients 38 clients that is as the data rate is increased only 38 clients are able to access the internet. In the data rate 3 only 28 clients are able to access the internet.

2.3 Reasons for Scalability and Fairness Issues

The main reason for the fairness/scalability problems is due to the contention of the channel by the clients. The contention of the channel is affected by many factors such as the gateway placement, error rate, traffic model, and the type of connection (TCP or UDP). TCP needs an acknowledgement for every packet, whereas UDP does not need an acknowledgement for every packet. The focus is mainly given on TCP connection in this article because as the TCP connection performance is increased in any model, the UDP performance is obviously increased. By the above results, we can see that network throughput or the unfairness in the hops depends on many factors, including data rate of the clients, placement of the routers/gateways, and error rate. Also, the throughput of the clients depends on different aspects such as traffic model used and type of connection used. The network must be scalable with the addition of clients but as the interference increases so the network overall throughput decreases.

2.4 Differentiated Clients Algorithm to Improve Scalability

2.4.1 Algorithm for scalability

The algorithm described here is completely dynamic as more and more nodes are added to the network at any instant of time so as to make the network scalable.It is evident that the throughput in a wireless network is related to interference and transmission time. As the nodes are added to the existing wireless mesh network the interference increases among the nodes. Therefore as the number of nodes increase the throughput decreases. In this section we focus on improving the throughput by reducing the interference. In order to increase throughput (capacity), we need to decrease the interference by some ways. We got an idea from the sleeping node in SMAC, which is for energy saving while waiting for wake-up. Our approach to decrease interference is implemented by stopping transmission of an application and buffering for some time. It seems to be similar to sleeping node, but different. Controlling of nodes is done in a periodic way so that no nodes are affected in a negative way. There are many types of applications and we classified them in to two types: high data rate applications and low data rate applications. Of course the high data rate applications demand more capacity of the channel than low data rate ones. So we use the low data rate applications to reduce the interference and increase the overall throughput of network. Firstly, applications with lesser data transfer rate are identified. The less data transfer rate applications are text messaging, browsing etc and high data rate applications are video streaming, online TV, download of huge files etc. Secondly, transmitting nodes with lesser data rate transfer are momentarily stopped and data is maintained in output buffer. The nodes are controlled in a periodic way so that each low data rate node is affected in the algorithm once or twice so that its performance is not deteriorated. The algorithm is completely dynamic and the low data rate nodes are controlled based on different factors such as the number of clients in the network, average network throughput and the number of transmitting nodes in the vicinity of the low data rate clients.

We used the network simulator ns2 tool for implementing our idea. The topology is given below. We simulated a base total of 100 802.11 nodes of which 64 are mesh clients and remaining act as mesh routers. Some of the mesh routers act as gateways through which the traffic flows to and from the internet. In the network region the gateway mesh routers are considered to be the final destinations. The gateways are connected to the internet by using wired connections. The wired connections from the gateways to the internet support huge data rates and very less error rates. The mesh routers that act as the gateways are chosen at a proper locations in the environment so that the clients are not too far away from the gateways. The gateways are to be chosen so that as more and more nodes are added to the network environment the clients are still able to access the internet regardless of the interference problems. In our experiment among the 64 mesh clients 32 clients

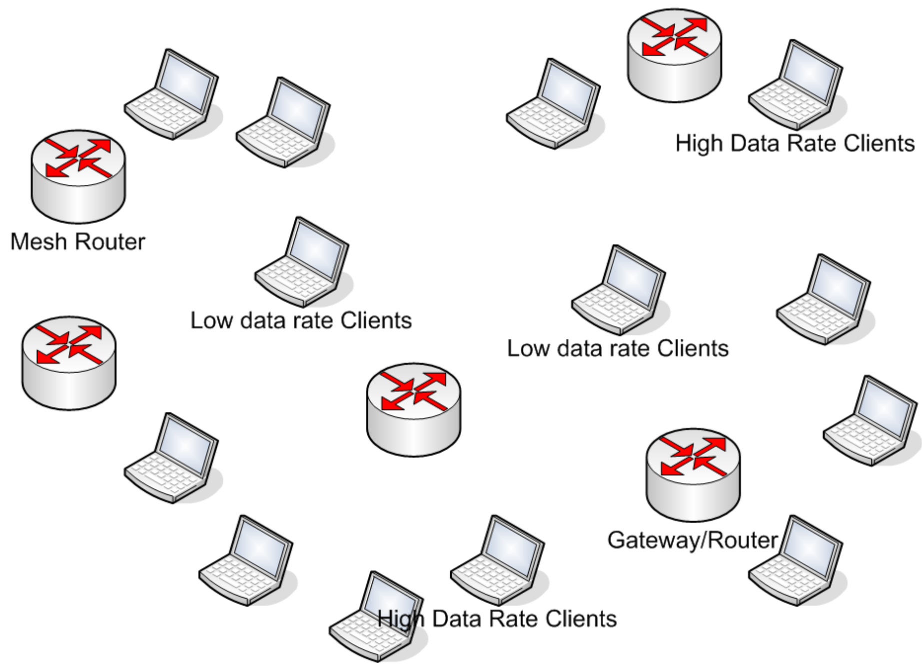

Figure 2.9: Experimental setup for Scalability Issue

are chosen as high data rate applications and 32 are chosen as low data rate applications. More and more nodes are added on and off in general case so as to make the network scalable. In general the different clients transfer at a different data rate based on the needs of the user. The clients are distributed uniformly in the entire network environment regardless of the high data rate or low data rate. The experimental setup is as shown below in Figure 2.9.

The simulation procedure is as follows: N Clients N/2 high data rate and N/2 low data rate Step1: All N active clients Step2: 3N/4 active clients (N/4 low data rate active) Step3: N/2 active clients (N/2 low data rate inactive)

The above procedure is explained as follows in the step1 all the clients are active that is there is no algorithm implemented in the step1. In general the network performance is determined based on the actual environment. In this case all the 64 mesh clients are active, none of the low data rate mesh clients are controlled.

In the step2 N/4 low data rate clients are controlled based on the vicinity of the client, average network throughput and the number of high data rate clients that are actually transmitting data. In this case 8 low data rate clients are controlled in a period way out of the 32 low data rate clients. The 8 low data rate clients are controlled in such a way that none of the performance is deteriorated. The application is buffered and made sure the packet reaches before the end of the timer in a TCP connection.

In the Step3 N/2 low data rate clients are controlled based on the algorithm procedure so as to improve the performance of the overall network. In this case 16 low data rate clients are controlled.

In the above cases more and more nodes are added to the network environment at any instant making the network scalable. The number 'N' is varied in real world environment from time to time.

We compared the throughput in the three cases and we got the results as follows. We analyzed our idea for mobile nodes and stationary nodes. The simulation results are as shown in the Figure 2.10.

As seen in the experimental results the throughput of different clients is varied in all the above 3 steps. In this case the overall average network throughput is also increased in the 3 steps.The overall average network throughput variation in all the above three steps is as shown in the figure 2.11.

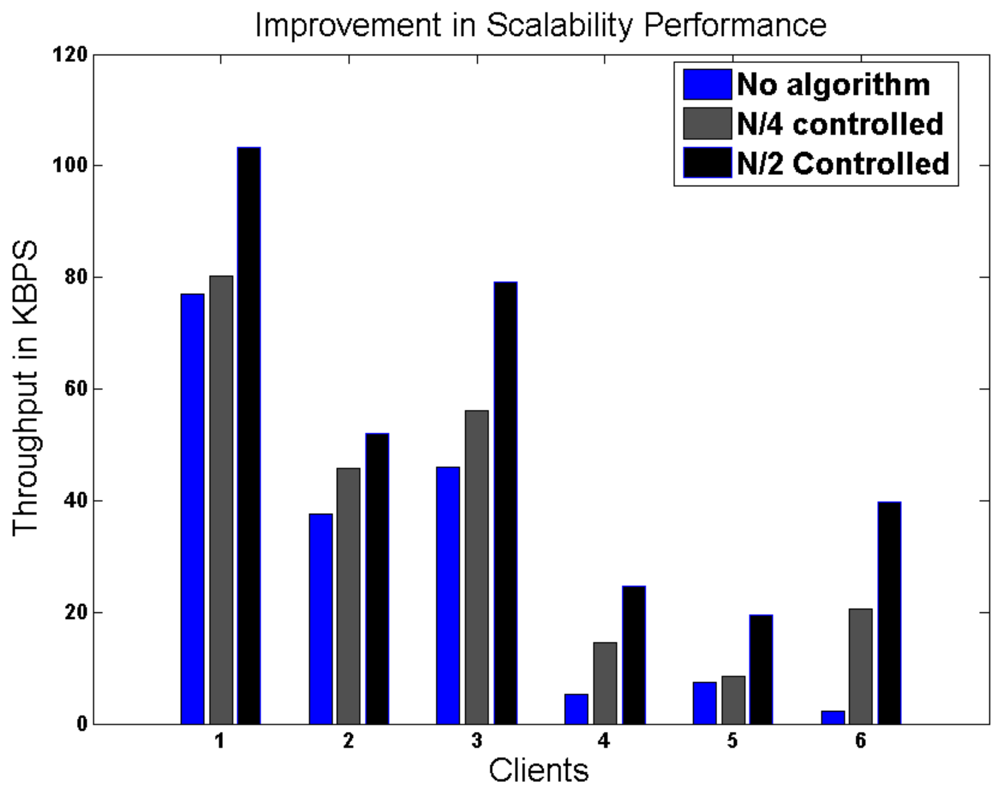

Figure 2.10: Performance of scalability algorithm

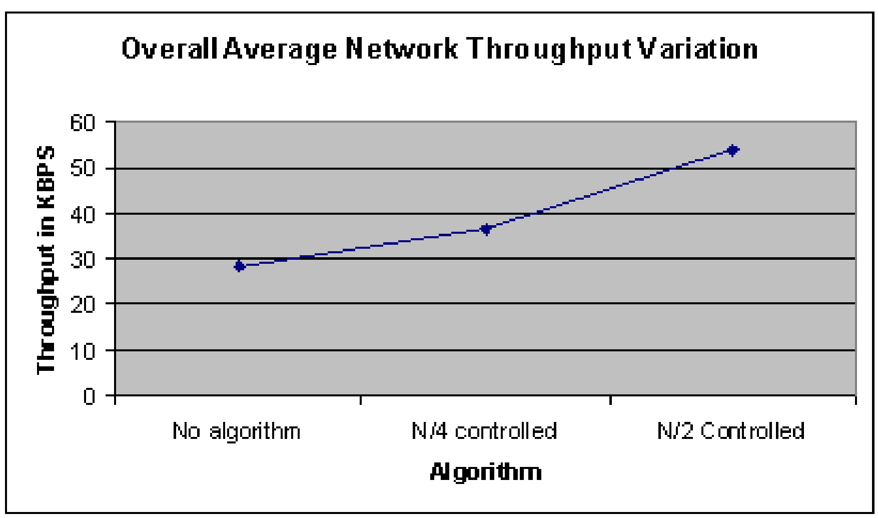

Figure 2.11: Performance of scalability algorithm Overall Average Network Throughput

CHAPTER 3

STUDY FAIRNESS IN WIRELESS MESH NETWORKS USING NS-2 SIMULATIONS

3.1 Definition of Fairness in Wireless Mesh Networks

In wireless mesh networks the nodes farther away from the gateway may be starved by nodes closer to the gateway[3]. This is due to the fact that the clients that are farther hops away exhibit frequent exponential back off. This leads to a higher probability of collision and loss, and a corresponding throughput decrease. This leads to unfairness among different clients in different hops in sharing of the throughput of the channel.

3.2 Related Work in Fairness Issue

There are various methods proposed to modify the back-off algorithm and contention windows for improving fairness which can be found in [59] [61]. One more approach NAV-blocking in which each Access Point transfers a beacon which does not allow the mobile stations to transmit during that interval [7]. The Forced Handoff technique forces the mobile stations between different Base Stations to switch between different base stations to achieve a fair throughput [7]. We used a Gateway Classification Algorithm in which the gateways are differentiated to handle different types of traffic.

3.3 Analysis of the Fairness Issue

In cellular networks, the network area is divided in to cells and each mobile user is only one hop away from its base station [11]. The other mobile users need not transmit the traffic of other mobile

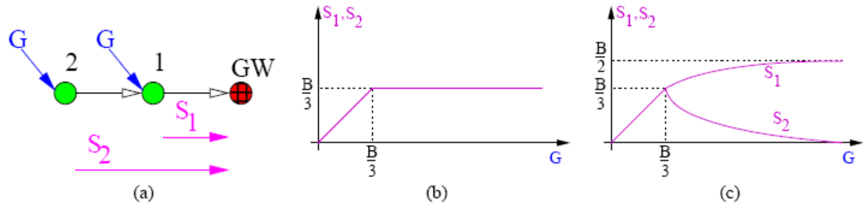

Figure 3.1: Idle vs Practical Fairness [2]

users to the base station. But in a wireless mesh network environment a mobile client user node has to transmit relayed traffic and also its own traffic. In a wireless mesh network the mesh clients contend among one another for the destination node or mesh router which transmits the traffic to the gateway and also between its traffic and the relayed traffic [2]. The contention environment is different in wireless LANs in infrastructure mode and cellular networks because the user nodes are only at one-hop distance from the access point and base station respectively[2].

The fairness problem is clearly explained by the Figure 3.1[2] there are two nodes,node 1 and node 2 which are offered a load of G. The destination node for the two nodes is the gateway node (GW) as shown in the figure. In the ideal case the channel is shared equally among the 2 nodes as the offered load (G) increases as shown in the Figure 3.1. But in practical case as the mesh clients have to contend between the relay traffic and its own traffic the node that is closer to the gateway node 1starves the node far away from the gateway The result in Figure 3.1 is obtained under the fact that the traffic to be forwarded by node 1 originating from the node 2 is queued together with the traffic from its own node 1[2]. So the correlation between different mesh clients fail to provide end-to-end fairness in multihop wireless mesh networks.

In a Wireless Mesh Network, there are several gateways. The gateways along with the mesh routers form a multi-hop environment for the mesh and conventional clients. We consider the topology as shown in the following Figure 3.2.

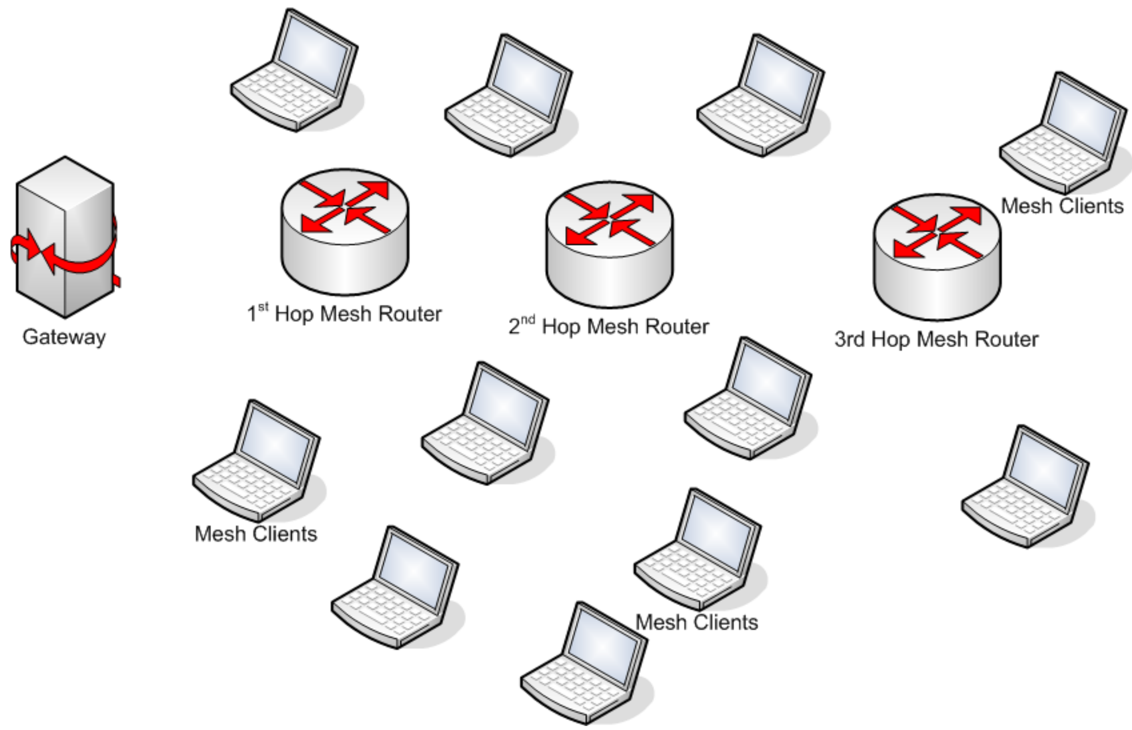

Figure 3.2: Experimental Setup Demonstrating Fairness

The topology consists of a gateway and mesh routers which form the multi-hop environment. The clients shown in the Figure 3.2. can communicate to the gateway through the mesh routers. The clients that are not within the reach of mesh router communicate with different mesh clients to forward the packets to the mesh router. Each client operates not only as a host but also a router forwarding packets on behalf of other clients. The clients in each hop are traveling at different speeds, ranging from pedestrian to vehicular speeds. Also, the clients are communicating to the gateway connected to the Internet at different data rates. Each client can access different applications such as browsing, text message, online TV, download of huge files which require different data rates for different clients. We used network simulator (NS-2) for simulation. The connection used here is a TCP connection in which the packets are acknowledged. The clients here are of different data rates to match to the traffic of the different users such as video streaming, text messaging. The throughput of different clients belonging to different hops is measured. The communication used

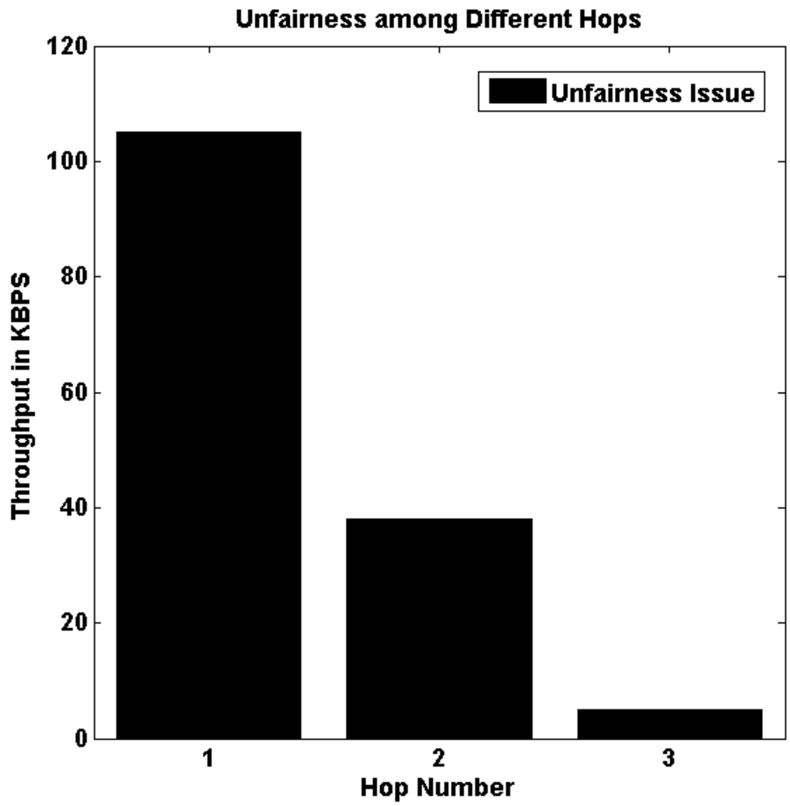

Figure 3.3: Unfairness Issue

here is a TCP communication which requires all the packets to be acknowledged back to the client. The transmission time for each successful packet is the total time in between release of the packet from the client and the time in which the acknowledgement is received. The throughput variation of the different hop clients is shown in Figure 3.3.

The Figure 3.3. shows that the throughput varies among different hops. The farther away hops experience frequent exponential back-off than the nearby hops as stated in [3]. The farther away hops from the gateway are starved due to the near hops from the gateway. The throughput variation of the first and the third hops differs a lot as shown in the Figure 3.3.

As the data rate of clients increases the far away hops are starved. If the data rate of the clients is very less than the clients up to 5th or 6th hops can access the gateway. The Lagrange polynomial

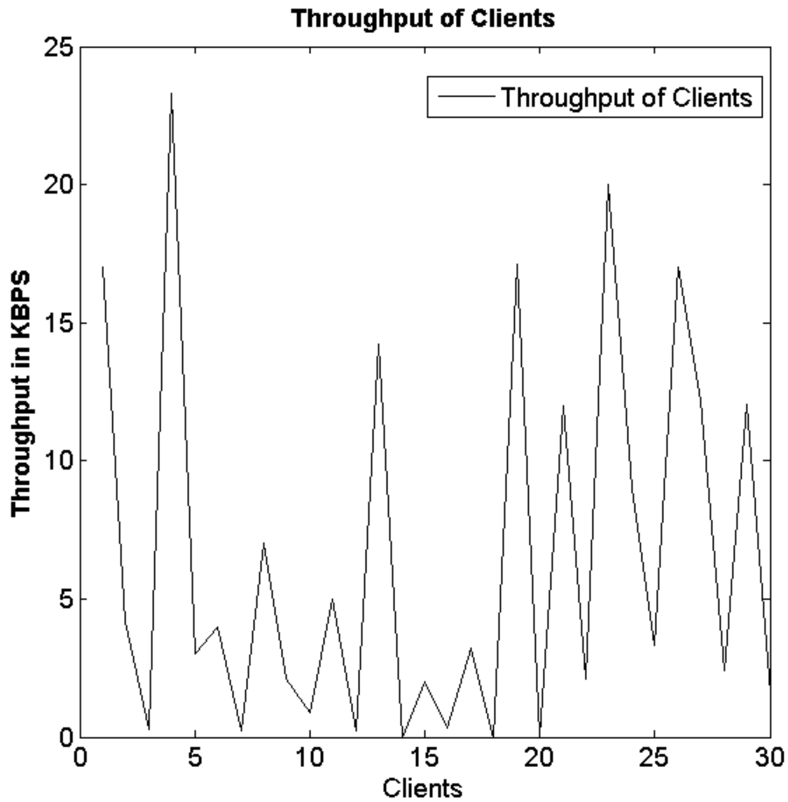

Figure 3.4: Throughput of Different Clients

as described in chapter 2 can also be used here to find the equation of the hop throughput for general nth hop.

A simulation environment with 100 mesh clients traveling at different speeds and 30 mesh routers in which three routers (10 percent of the total routers) act as gateways are randomly deployed and the performance of the clients is measured. It is observed that different clients have different throughputs which demonstrates the unfairness issue. As seen from the Figure 3.4. eventhough all the clients are in the same network area they are not able to share the resources fairly. The throughput varies depending on the hop of the client as illustrated in Figure 3.4.

3.4 Unfairness in Different Traffic Models

3.4.1 Different Traffic Models

There are different types of traffic models used in the real network environment such as Exponential, Pareto and CBR.

The Exponential ON/OFF traffic generator in a simulation environment has different parameters such as packetsize,bursttime, idletime and rate. The burst time is the average 'on' time for the traffic generator, the idle time is the average 'off' time for the generator and rate is the sending rate of the packets during the 'on' time [48].

In ns-2 simulation environment the Exponential On/Off generator can be made to work as a Poisson generator by changing the variable bursttime to 0 and by changing the variable rate to a very large value. The C++ code ensures that even if the burst time is set to zero, at least one packet is sent [48]. And also the next interarrival time is the sum of the assumed packet transmission time and the random variate corresponding to idle time[48]. To make the first term in the sum very small, make the burst rate very large so that the transmission time is almost zero compared to the typical idle times [48].

The CBR traffic generator has different parameters such as packetsize, rate and random. The rate is the constant rate at which the packets are sent, random is the flag indicating whether or not to introduce random “noise” in the scheduled departure times [48].

The fairness issue is demonstrated for different types of user traffic models. The exponential and CBR traffic models are used as the user traffic. The following results show the Unfairness for different traffic models. In the first case Figure 3.5 all the clients use Exponential traffic and in the second case Figure 3.6 all the clients use CBR traffic. As seen from the results both the exponential and CBR traffic models have unfairness issue in the hops. If there is some factor to control the

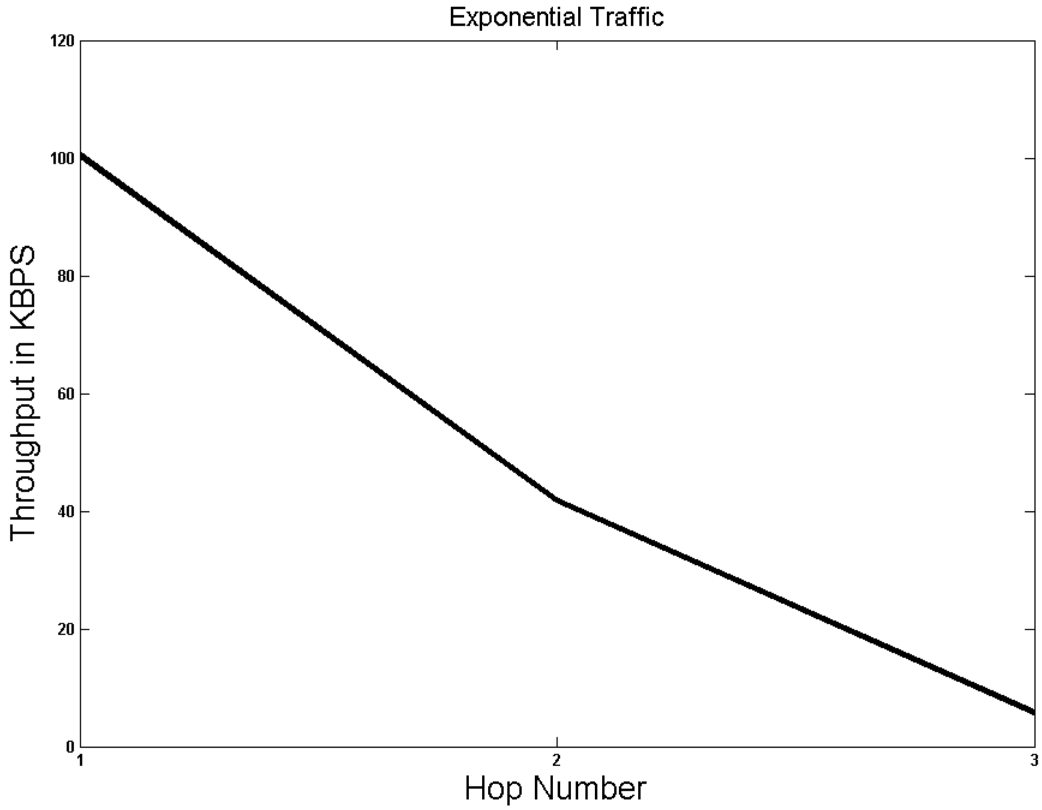

Figure 3.5: Variation of Hop Performance for Exponential Traffic

network traffic, we could have avoided the fairness to some extent. There is no factor as to control the unfairness in these type of traffic models.

Earlier in this section we performed the experiment on Exponential and CBR traffic models. Now we have focused our attention on the Pareto Traffic Model which allow us to modify some factors to improve the fairness of the far way hops. The Pareto On/Off Traffic Generator is a traffic generator embodied in the OTcl class Application/Traffic/Pareto. It generates traffic according to a Pareto On/Off distribution. Packets are sent at a fixed rate during on periods, and no packets are sent during off periods. Both on and off periods are taken from a Pareto distribution with constant size packets. These sources can be used to generate aggregate traffic that exhibits long range dependency. There are various input parameters in the pareto traffic model such as burst time,

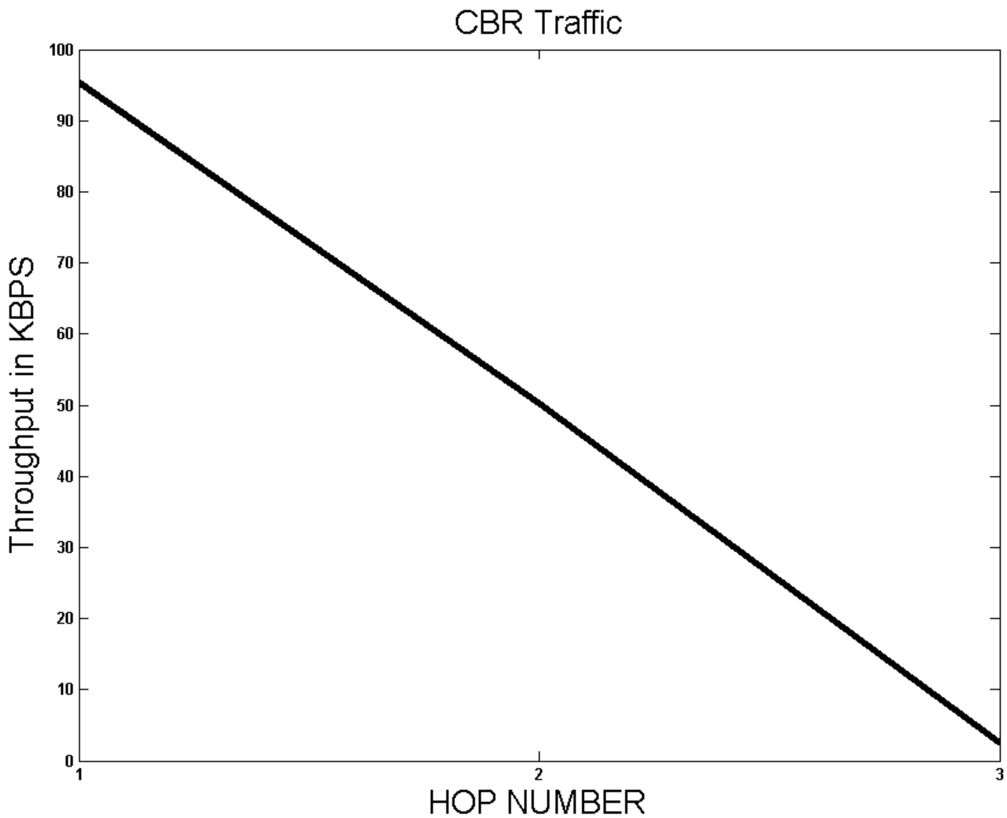

Figure 3.6: Variation of Hop Performance for CBR Traffic

idle time, rate, packet size and shape. In each On/Off round the next burst time and next idle time are computed based on the pareto shape parameter. The next burst time refers to the number of packets to be transmitted in the next burst period. Based on the characteristics of the pareto traffic model the numbers of packets send during the on-time of an application can be varied.In a Wireless Mesh Network as we know the farther away hops are starved by the hops closer to the gateway. Using the characteristics of pareto traffic model the farther away hops are made to send more number of packets during the on period than the hops that are closer to the gateway by varying the pareto shape parameter. This improves the performance of the far away hops as compared to without using this algorithm. Now here the Pareto shape parameters are setup in such a way that the clients that are father hops away from a gateway are made to send more number of packets during the on time as compared to the clients that are nearer to the gateway. This algorithm is applied to observe the improvement in the performance of the far away hops. The experimental results are as shown in Figure 3.7.

3.5 Gateway Classification Algorithm (GCA)

In Chapter 2 the network performance is observed by properly placing the gateways in a network environment, the gateways are not classified into different types. The results are obtained by changing the position of the gateways. In the results, we can observe a change in the throughput of the overall network. This gave us an idea that the gateways can be modified in order to vary the network performance. In this section, we classify the gateways into different types. In a wireless mesh networks, there are several gateways. We classify the gateways into two types: high data rate gateways and low data rate gateways. The high data rate gateways are responsible for handling the traffic of the high data rate clients. The low data rate gateways are responsible for handling the low data rate clients. By classifying the gateways into these two types, we can improve the performance in terms of fairness. The traffic from the clients is routed to the appropraite gateway based on the

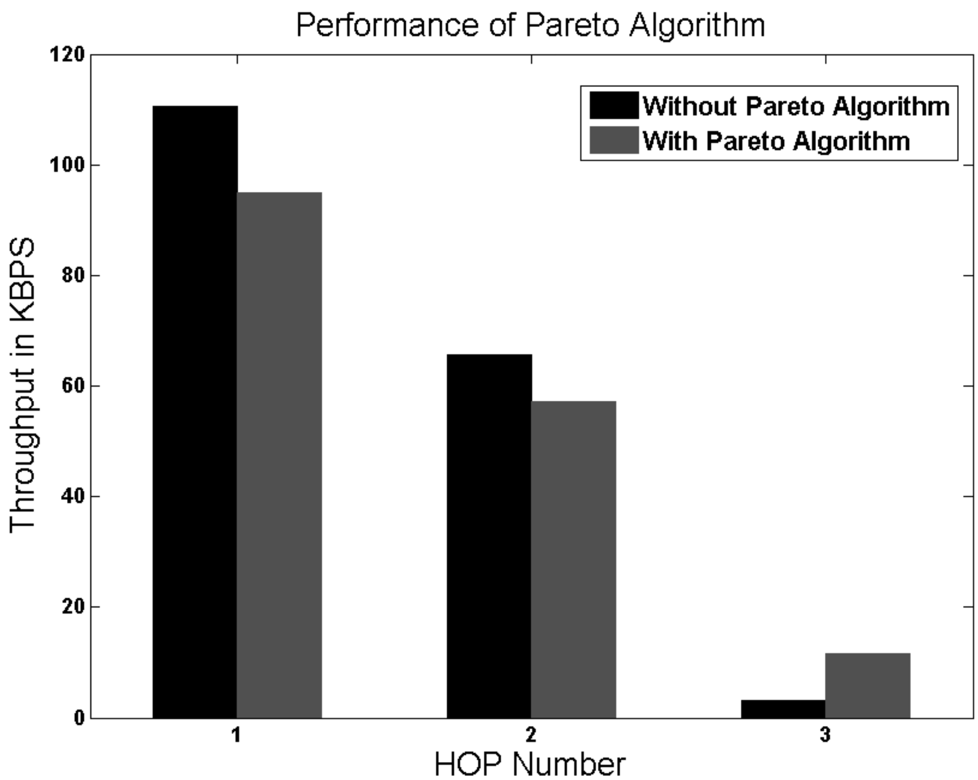

Figure 3.7: Improvement in Hop Performance using Pareto Traffic Model

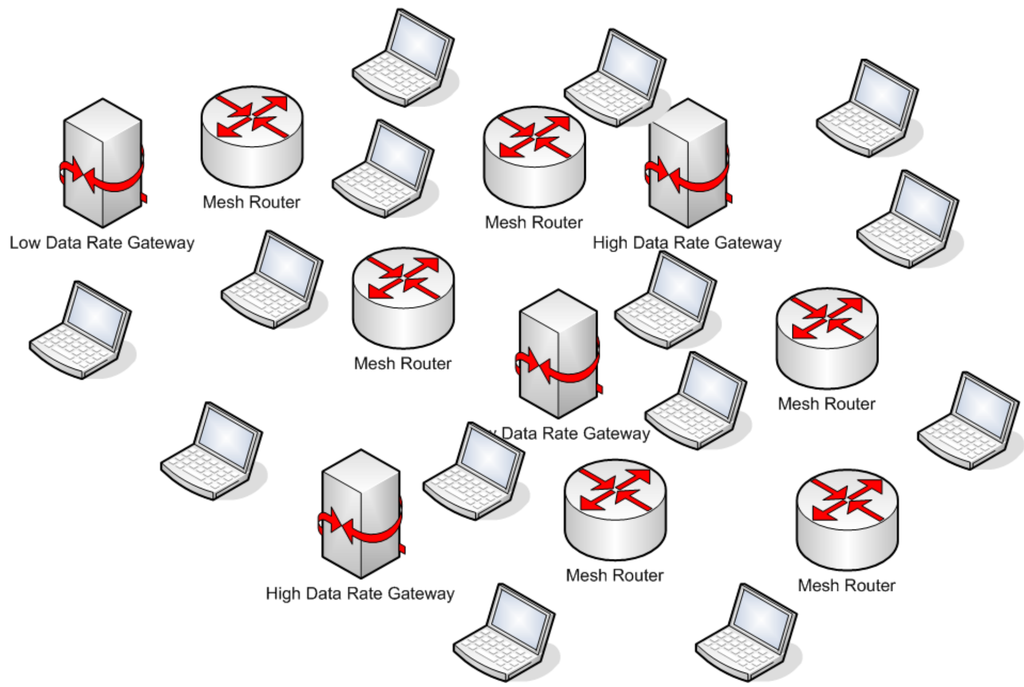

Figure 3.8: Experimental Setup for Gateway Classification Algorithm

traffic of the clients. As shown in the experimental setup, the gateways are classified and the traffic is routed to an appropriate gateway. A number of experiments have been performed to study the fairness issue using the proposed GCA. As stated earlier, the ns-2 simulator is used to perform the experiments. The experimental setup is depicted in Figure 3.8.

The gateways as indicated in the figure are classified in to two types. The improvement of the overall network performance is shown in Figure 3.11.

The Experimental results during the different iterations are as shown in the figure. The Experiment is iterated for a total runs of 100 and the average of all the results is shown in the Figure 3.9. The results of some of the interations are as shown in the Figure 3.10.

As shown in the experimental setup, the different clients are routed to different gateways. The clients are now neither far away nor near as in the normal architecture as the gateways are distributed throughout the entire network. The traffic is routed in such a way that all the low data rate traffic is routed to one of the type of gateways and all high data rate traffic is routed to other

Iteration	1^{st} HOP	2^{nd} HOP	3^{rd} HOP
1	106.67	40.75	6.02
2	105.09	39.21	5.93
3	106.77	40.09	5.32
4	106.0	38.7	6.27
5	105.71	40.051	6.73
6	106.12	39.231	5.05
7	105.83	40.81	5.49
8	106.12	40.0	5.3711
9	105.02	40.18	6.373
10	105.68	39.902	5.402

Figure 3.9: Results of Iterations without Using Gateway Classification Algorithm

Iteration	1^{st} HOP	2^{nd} HOP	3^{rd} HOP
1	57.3	41.94	32.58
2	58.61	39.72	33.0
3	59.501	36.39	33.52
4	59.22	37.92	31.74
5	60.31	41.68	32.602
6	56.803	39.0	31.405
7	57.427	41.24	32.4
8	58.502	36.48	36.32
9	58.418	35.92	29.41
10	58.715	39.51	27.802

Figure 3.10: Results of Iterations with Using Gateway Classification Algorithm

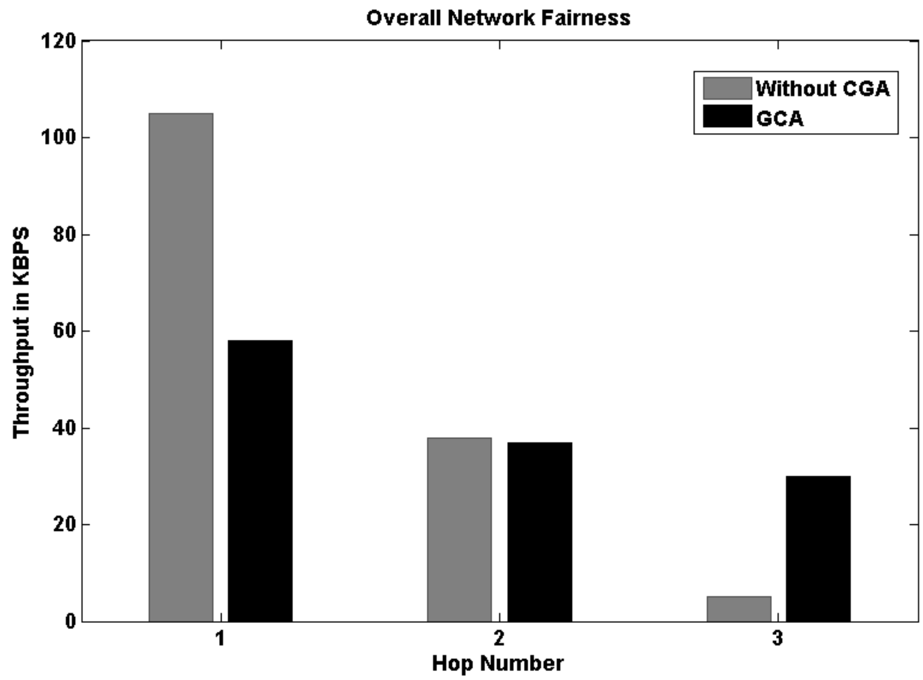

Figure 3.11: Throughput Variation Using Gateway Classification Algorithm

type of gateways. The clients do not experience the exponential back-off frequently as in the normal architecture. Because of this, the throughput of the overall network is distributed in a reasonable manner. As depicted in the Figure 3.12., the variation of the throughput of the clients in the two different cases and the overall performance distributed in a fair manner. The variation of throughput of different clients is shown in Figure 3.12.

In the above Figure 3.12. the variation of throughput of each individual client is observed after the implementation of the algorithm. It can be obviously seen that the performance of each client is improved based on the gateway classification algorithm.

The histogram in Figure 3.13. shows the number of clients at different throughput ranges.

We can observe the increase in the number of clients in the range of 2nd hop throughput. As shown in the Figure 3.13., the throughput variation is huge. Without GCA the number of clients in the throughput range (0-10) are 83. After the application of the proposed GCA, the number of

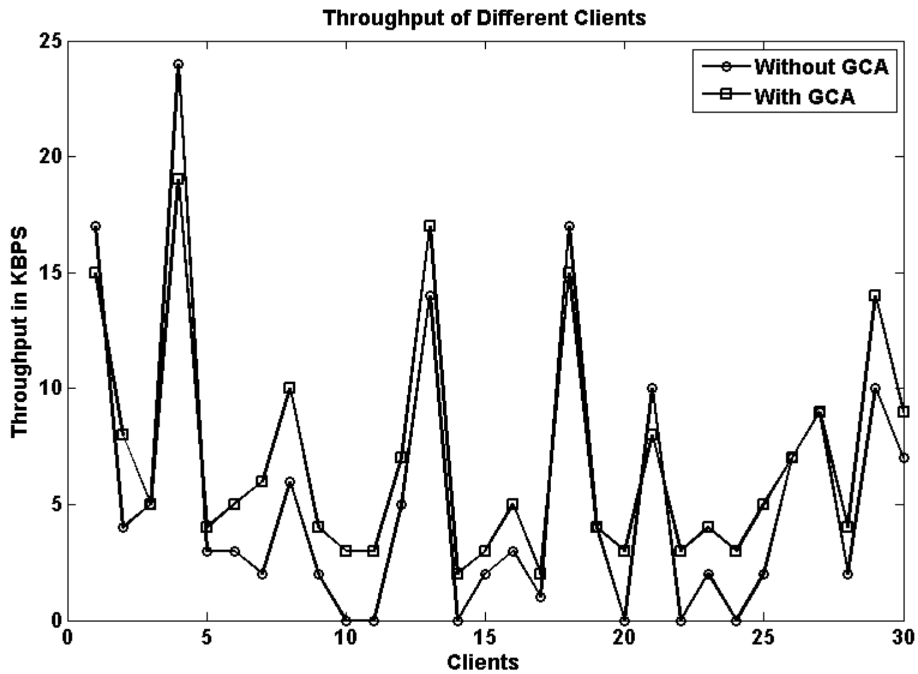

Figure 3.12: Improvement in Throughput for Different Clients

clients are only 23. This shows that more clients that are in the lower data rate range are shifted to the higher data rate range, which supports the fact that more channel share is provided to those clients. Also, the number of clients in the throughput range of (10-20) are increased from 13 to 68. With the proposed GCA, the throughput of the 3rd hop clients is almost increased three times. In our simulation results the network performance of the third hop clients is improved by a factor of 6.5.

With the implementation of the Gateway Classification Algorithm the throughput of the far away hops can be significantly improved and the overall network performance can be fair. The algorithm proposed can be implemented without the need for additional resources and by changing the protocols involved in the network environment.

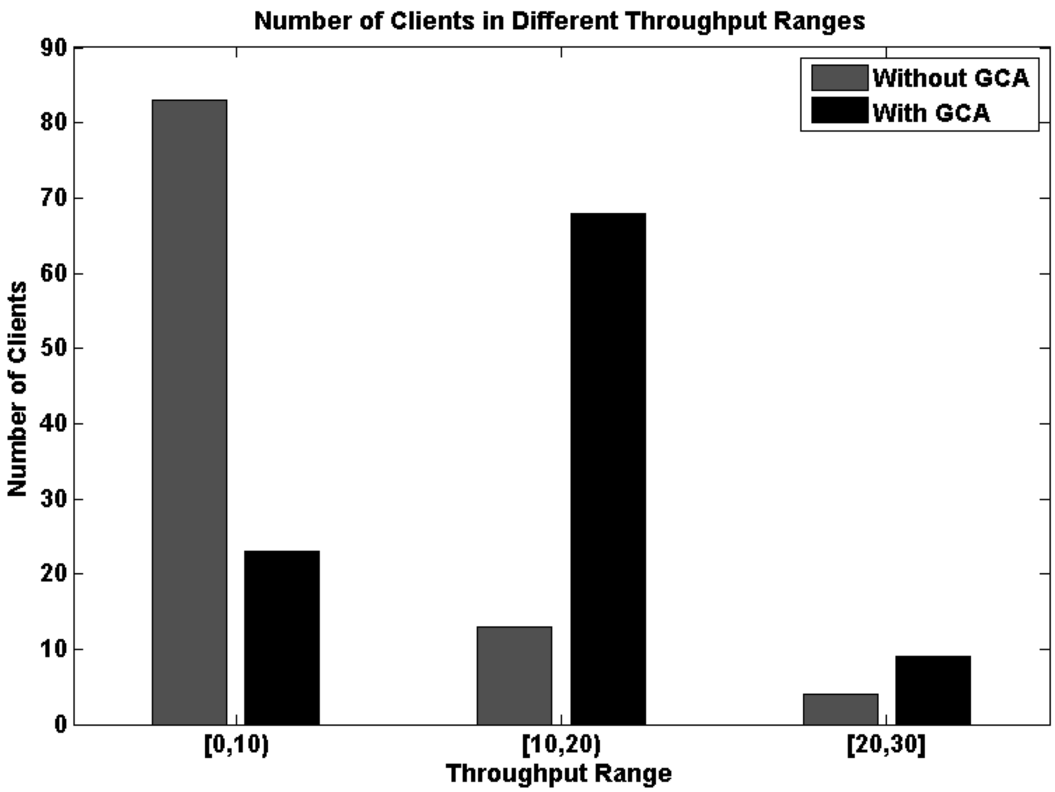

Figure 3.13: Histogram Showing Performance of Number of Clients

CHAPTER 4

CONCLUSION

Wireless mesh networks have many advantages, and also there are other issues which need more investigation. Other issues associated with the mesh networks are scalability, mobility, unfairness and security. More investigation is needed in these areas. In the first chapter of this thesis, we presented the characteristics, applications and problems associated with wireless mesh networks.

In the second chapter we analyzed the variation of the performance of wireless mesh networks with respect to different parameters such as error rate, gateway placement, data rate of clients. In this chapter we also demonstrated the scalability issue and proposed a differentiated clients algorithm to solve the scalability problem. The algorithm proposed is a dynamic algorithm and the performance improves as more and more mesh clients are added to the network environment. The algorithm is verified using the NS-2 simulation environment and the results obtained show a significant improvement in the performance.

In the third chapter the unfairness in multi-hop wireless mesh networks is introduced and the performance of different traffic models such as the exponential, Constant Bit Rate and the Pareto traffic models on different hops is observed. Finally a Gateway classification algorithm is proposed which differentiates the gateways in the environment and the traffic is routed to the appropriate gateway. The simulation is performed using ns-2 simulator and the results obtained show a significant improvement in the performance of the far way hop clients. In the future the improvement in throughput performance when both, differentiated client and differentiated gateway algorithms are employed will be studied and heterogenous clients will be deployed to emulate realistic scenarios.

Bibliography

[1] I.F. Akyildiz and X. Wang, "A Survey on Wireless Mesh Networks," IEEE Communications Magazine, September 2005.

[2] J. Jun, "The nominal capacity of wireless mesh networks," Wireless Communications, IEEE Volume 10, Issue 5, September 2005.

[3] V. Gambiroza, B. Sadeghi and E. Knightly, "End-to-End Performance and Fairness in Multi-hop Wireless Backhaul Networks," Proceedings of ACM MobiCom 2004, Philadelphia, PA, September 2004.

[4] C.W. Hsu, C.Y. Wang and T.C. Hou, "Providing End-to-End Fairness in Wireless Mesh Networks with Chain Topologies," Parallel and Distributed Computing and Systems, November 2006.

[5] N. Bisnik, and A. Abouzeid, "Delay and throughput in random access wireless mesh networks," Proceedings of IEEE International Conference on Communications ICC'06, June 2006.

[6] D. Zhao, "Inter-AP coordination for fair throughput in infrastructure-based IEEE 802.11 mesh networks," International Conference on Wireless Communications and Mobile Communications, Vancouver, Canada, July 2006.

[7] D. Zhao, "Achieving fair throughput in infrastructure-based IEEE 802.11 mesh networks," IEEE GLOBECOM'06, December 2006.

[8] R.G. Cheng, C.Y. Wang and L.H. Liao, "Ripple: A Distributed Medium Access Protocol for Multi-hop Wireless Mesh Networks," Vehicular Technology Conference, September 2006.

[9] B. Braunstein, T. Trimble, R. Mishra, B.S. Manoj and R. Rao, "On The Traffic Behavior of Distributed Wireless Mesh Networks," International Symposium on a World of Wireless, Mobile and Multimedia Networks, June 2006.

[10] R. Cheng, C. Wang, L. Liao, and J. Yang, "Ripple: A wireless token-passing protocol for multi-hop wireless mesh networks," Communications Letters, IEEE, September 2006.

[11] N.B. Salem and J.P. Hubaux, "Securing wireless mesh networks," Communications Letters, IEEE, September 2006.

[12] B. Aoun, R. Boutaba and G. Kenward, "Analysis of Capacity Improvements in Multi-Radio Wireless Mesh Networks," Vehicular Technology Conference, September 2006.

[13] R.K. Lam, D. Chiu and C.S. Lui, “On the Access Pricing Issues of Wireless Mesh Networks,” International Conference on Distributed Computing Systems, July 2006.

[14] T. Wu, Y. Xue and Y. Cui, “Preserving Traffic Privacy in Wireless Mesh Networks,” International Symposium on a World of Wireless, Mobile and Multimedia Networks, June 2006.

[15] A. Acharya, A. Misra and S. Bansal, “Design and analysis of a cooperative medium access scheme for wireless mesh networks,” First International Conference on Broadband Networks, 2004.

[16] R. Luo, D. Belis, R.M. Edwards and G.A. Manson, “simulation design for link connection-oriented wireless mesh networks,” 4th International Workshop on Mobile and Wireless Communications Network, 2002.

[17] P. Beckman, S. Verma and R. Rao, “Use of mobile mesh networks for inter-vehicular communication,” Vehicular Technology Conference, 2003.

[18] A. Raniwala and T. Chiueh, “Evaluation of a wireless enterprise backbone network architecture,” 12th Annual IEEE Symposium on High Performance Interconnects, 2004.

[19] S. Naghian, “Mesh vs. point-to-multipoint topology: a coverage and spectrum efficiency comparison,” 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2004.

[20] L. Iannone, R. Khalili, K. Salamatian and S. Fdida,“Cross-layer routing in wireless mesh networks,” International Symposium on Wireless Communication Systems, 2004.

[21] A. Adya, P. Bahl, J. Padhye, A. Wolman, L. Zhou, “A multi-radio unification protocol for IEEE 802.11 wireless networks,” First International Conference on Broadband Networks, 2004.

[22] F. Tasaki, H. Tamurat, M. Sengokut and S. Shinodas, “A new channel assignment strategy towards the wireless mesh networks,” 5th International Symposium on Multi-Dimensional Mobile Communications Proceedings, 2004.

[23] P.H. Hsiao and H.T. Kung, “Layout design for multiple collocated wireless mesh networks,” Vehicular Technology Conference, 2004.

[24] M.K. Marina and S.R. Das, “A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks,” 2nd International Conference on Broadband Networks, 2005.

[25] V. Navda, A. Kashyap and S.R. Das, “Design and evaluation of iMesh: an infrastructure-mode wireless mesh network,” IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks, 2005.

[26] A.K. Das, H.M. K. Alazemi, R. Vijayakumar and S. Roy, “Optimization models for fixed channel assignment in wireless mesh networks with multiple radios,” 2005 Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2005.

[27] B. Ji, "Asynchronous wireless collision detection with acknowledgement for wireless mesh networks," Vehicular Technology Conference, 2005.

[28] L. Liu and G. Feng, "Research on Multi-constrained QoS Routing Scheme Using Mean Field Annealing," Sixth International Conference on Parallel and Distributed Computing, Applications and Technologies, 2005.

[29] C. Zhu, M.J. Lee and T. Saadawi, "On the route discovery latency of wireless mesh networks," Consumer Communications and Networking Conference, 2005.

[30] K. Balaji, N. Hegde, B. Venkata Ramana, B. S. Manoj, and C. Siva Ram Murthy,"Performance evaluation of a hybrid wireless network architecture for rural communication," IEEE International Conference on Personal Wireless Communications, 2005.

[31] F.H.P. Fitzek, T.K. Madsen, R. Prasad and M. Katz, "Cooperative IP header compression for parallel channels in wireless meshed networks," IEEE International Conference on Communications, 2005.

[32] P.M. Ruiz and A.F. G. Skarmeta, "Approximating optimal multicast trees in wireless multihop networks," IEEE Symposium on Computers and Communications, 2005.

[33] R. Liscano, E.F. Sadok and E.M. Petriu , "Mobile wireless RSA overlay network as critical infrastructure for national security," IEEE International Workshop on Measurement Systems for Homeland Security, Contraband Detection and Personal Safety Workshop, 2005.

[34] I.F. Akyildiz, "Key technologies for wireless networking in the next decade," International Conference on Pervasive Services, 2005.

[35] L. Fu, Z. Cao and P. Fan, "Spatial reuse in IEEE 802.16 based wireless mesh networks," IEEE International Symposium on Communications and Information Technology, 2005.

[36] S. Thuel and R. Cruz, "The next big bang in wireless and mobile communication," 14th International Conference on Computer Communications and Networks, 2005.

[37] K.N. Ting, Y.F. Ko and M.L. Sim, "Voice performance study on single radio multi-hop IEEE 802.11b systems with chain topology," 13th IEEE International Conference on Networks jointly held with IEEE 7th Malaysia International Conference on Communication, 2005.

[38] C.E. Seo, E.J. Leonardo, P. Cardieri, M.D. Yacoub, D.M. Gallego and A.A.M. de Medeiros, "Performance of IEEE 802.11 in wireless mesh networks," International Conference on Microwave and Optoelectronics,2005.

[39] W. Allen, A. Martin, A. Rangarajan, "Designing and deploying a rural ad-hoc community mesh network testbed," The IEEE Conference on Local Computer Networks, 2005.

[40] Y. Ma, "Improving wireless link delivery ratio classification with packet SNR," International Conference on Electro information Technology, 2005.

[41] G. Goth, "Groups hope to avoid mesh standard mess," Distributed Systems online, IEEE 2005.

[42] B. Cheng, S. Kalyanaraman and M. Klein, “A geography-aware scalable community wireless network test bed,” First International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, 2005.

[43] I. Aydin, C. Jaikaeo, and C. Shen ,“Quorum-based match-making services for wireless mesh networks,” IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, 2005.

[44] J.A. Stine, “Exploiting smart antennas in wireless mesh networks using contention access,” Wireless Communications, IEEE, 2006.

[45] C. Ma, Z. Zhang and Y Yang, “Battery-aware router scheduling in wireless mesh networks,” 20th International Parallel and Distributed Processing Symposium, 2006.

[46] Jane- Hwa. Huang, Li-Chun. Wang and Chung-Ju. Chang, “Coverage and capacity of a wireless mesh network,” International Conference on Wireless Networks, Communications and Mobile Computing, 2005.

[47] T. Tsai and J. Chen, “IEEE 802.11 MAC protocol over wireless mesh networks: problems and perspectives,” 19th International Conference on Advanced Information Networking and Applications, 2005.

[48] NS-2 manual documentation, “http://www.isi.edu/nsnam/ns/doc/index.html”.

[49] M. Kodialam and T. Nandagopal, “Characterizing Achievable Rates in Multi-Hop Wireless Mesh Networks With Orthogonal Channels,” Transactions on Networking, IEEE, 2005.

[50] X. Tao, T. Kunz and D. Falconer,“Traffic balancing in wireless MESH networks,” International Conference on Wireless Networks, Communications and Mobile Computing, 2005.

[51] L. Liu and G. Feng, “Mean field network based QoS routing scheme in wireless mesh networks,” International Conference on Wireless Communications, Networking and Mobile Computing, 2005.

[52] Z. Lei, Y. ShouBao, S. Weifeng and W. DaPeng, “Markov-Based Analytical Model for TCP Unfairness over Wireless Mesh Networks,” First International Multi-Symposiums on Computer and Computational Sciences, 2006.

[53] B. Wehbi, W. Mallouli and A. Cavalli, “Light Client Management Protocol for Wireless Mesh Networks,” International Conference on Mobile Data Management, 2006.

[54] H. Viswanathan and S. Mukherjee, “Throughput-range tradeoff of wireless mesh backhaul networks,” IEEE Journal on Selected areas in Communications, 2006.

[55] N. Funabiki, S. Yoshida, S. Tajima and T. Higashino, “An Internet Gateway Access-Point Selection Problem for Wireless Infrastructure Mesh Networks,” 7th International Conference on Mobile Data Management, 2006.

[56] D.M. Shrestha and Y.B. Ko, “On Construction of the Virtual backbone in Wireless Mesh Networks,” The 8th International Conference Advanced Communication Technology, 2006.

[57] M.J. Lee, J. Zheng, Y.B. Ko and D.M. Shrestha, “Emerging standards for wireless mesh technology,” Wireless Communications, IEEE, 2006.

[58] T. Tsai, H. Tseng and A. Pang, “A new MAC protocol for Wi-Fi mesh networks,” 20th International Conference on Advanced Information Networking and Applications, 2006.

[59] R.E. Ludwig, “Eliminating inefficient cross-layer interactions in wireless networking,” Ph.D. dissertation, Aachen University of Technology, Germany, 2000.

[60] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: a media access protocol for wireless LANs, in Proc. of ACM SIGCOMM94, 1994.

[61] J. Liu and S. Singh, “ATCP:TCP for mobile ad hoc networks,” IEEE Journal on selected areas in communications, vol. 19, no. 7,pp, 1300-1315, July 2001.

[62] www.wikipedia.com, “http://upload.wikimedia.org/wikipedia/en/thumb/b/b1/Hidden-node.svg/524px-Hidden-node.svg.png”.

[63] www.wikipedia.com, “Exposed Terminal Problem”.

[64] A. Quarteroni, R. Sacco, and F. Saleri, “Numerical Mathematics (Texts in Applied Mathematics) (Hardcover)”, November, 2006.