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CHANNEL ALLOCATION IN AN OVERLAID MESH NETWORK

Master's Thesis for the degree Master of Science in Technology submitted for inspection, Vaasa, 12 November, 2008.

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FOREWORD

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CONTENTS

SYMBOLS

σ_x^2	Variance of service time
σ_y^2	Variance of inter arrival time of packet in the queue
ρ	Utilization factor
λ	Arrival rate of packet

ABBREVIATIONS

ACK	Acknowledgement
AIFS	Arbitrary Distributed Inter-Frame Space
ARF	Auto Rate Fallback
CBR	Constant Bit Rate
CCK	Complementary Code keying
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Code
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CTS	Clear to Send
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	Distributed Inter Frame Space
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhance Distributed Channel Access
EDCF	Enhanced Distributed Coordination Function
ERP	The Effective Radiated Power
ESMA	Efficient Mesh Security Architecture
ETT	Expected Transmission Time
ETX	Expected Transmission Count
FCS	Frame Check Sequence
FHSS	Frequency Hoping Spread Spectrum
HC	Hybrid Controller
HCF	Hybrid Coordination Function

HEC	Header Error Correction
HWMP	Hybrid Wireless Mesh Protocol
IEEE	Institute of Electrical and Electronic Engineers
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
LL	Link Layer
LQSR	Link Quality Source Routing
MAP	Mesh Access Point
MP	Mesh Point
MPDU	MAC Protocol Data Unit
MPP	Mesh Point Portal
NAV	Network Allocation Vector
NIC	Network Interface Card
NOAH	No Adhoc Routing Agent
NS2	Network Simulator
OFDM	Orthogonal Frequency Division Multiplexing
PCF	The Point Coordination Function
PHY	Physical
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
PMDU	Physical Medium Dependent Data Unit
RA	Receiver Address
RA-OLSR	Radio Aware Optimized Link State Routing
RTS	Request to Send
RTT	Round-Trip Delay Time
SFD	Start Frame Delimiter

SIFS	Short Inter Frame Space
SINR	Signal to Interference Noise Ratio
TA	Transmitter Address
TBRPF	Topology Broadcast Reverse Path Forwarding
TCP	Transmission Control Protocol
TG	Task Group
TMT	Theoretical Maximum Throughput
TXOP	Transmission Opportunity
VPN	Virtual Private Network
Wi-Fi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WMN	Wireless Mesh Network

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ABSTRACT:

In spite of recent advancement of Wireless Mesh Technology, a lot of research challenges remained to be solved to extract the full capacity of this modern technology. As 802.11a/b/g standards make available the use of multi radio multi channel in a wireless node, a lot of research activities are going on to efficiently allocate the channel of a Mesh Network to boost its overall performances. In this research, the prospect of dividing the total network area into two non-overlapping channels of a given Mesh Network is investigated and analyzed numerically. It is found that the throughput is doubled as well as the fairness improves considerably if we deploy two channels instead of single channel backbone. An extensive simulation study has been carried out to find the optimum coverage area between two channels. The study shows that at a particular point of allocation, the network gives the optimum response.

Keywords: Mesh Network, 802.11 a/b/g, Network Fairness

1. INTRODUCTION

The Wireless Mesh Network (WMN) is a decentralized, self–organized and adaptable networking technology consisting of mesh nodes that form the backbone of the network. It offers flexible broadband network configuration that is independent of fixed network. Due to these significant features, it is attracting the attention as an elemental technology for future ubiquitous networks consisting of various types of terminals including digital appliances, mobile terminals, personal computers etc. (Matsumoto 2006). Despite recent progress, a lot of research challenges remain to be solved to get the optimum performance from a wireless mesh. One of the challenges is the deployment of efficient channel allocation among the nodes. The IEEE 802.11 Wireless LAN standards permit the use of multiple non-overlapping channels simultaneously to enhance the performance. A mesh network serves as a backbone for relaying end–user traffic from the wireless access point to the control node. The concept of exploiting multiple channels is gaining significant attention among the researcher because of the high capacity requirement of the mesh backbone to support massive traffic. In this thesis the prospect of multi channel assignment based on the coverage area of a particular mesh topology has been analyzed numerically. A detailed performance evaluation shows that an efficient allocation of channels by equipping some mesh points with just two NICs operating on different frequency enhances the performance significantly compared with the traditional single channel backbone.

1.1. Motivation and Objective

In the last few decades a lot of advancements have occurred in the area physical layer technology. Yet, the Wireless LAN is incapable of providing the same level of performance as Wired LAN (Raniwala 2004:50-65). The theoretical maximum throughput of an IEEE 802.11 network in absence of transmission error and collision is around 54 Mbps (Jangun 2003). But if the medium access level collision, ACK, 802.11 headers, fragmentation, frame error etc. are considered, the actual throughput experienced by an application becomes a fraction of the proposed theoretical level. Apart from this, if the distance between two nodes increases the data rate falls rapidly. The performance becomes further worse for the multi-hop network as the interference comes from the neighboring nodes. Under the above circumstances, facility to use multiple channels available in 802.11a/b/g standard enhances the useful bandwidth available to the wireless nodes significantly.

In this research work, we tried to deploy the facility of using multi channel in a single channel mesh network to have better performance. The mesh network here consist of around hundred static stations (STA) uniformly distributed in a 400×400 square meter premises. The backbone of the network is made of 16 mesh points functioning as both router as well as access point to the STAs. The MPs are equipped with two radios and the STAs are equipped with single radio multi-channel NIC. Throughout the experiment we tried to find out the answer of the following questions.

- How could the two channels in the mesh be allocated to have optimum throughput, delay and jitter?
- Does the performance really increase after introducing multi channel multi radio?
- What about the routing strategy?
- Are all STAs getting equal facilities? i.e.; is the system fair?
- Is there any bottleneck? If any, how can we get rid of it?
- What are the key parameters influencing the mesh performance?

As a whole, the objective of the work is to divide the coverage area between two channels in such a way so that the optimum performance in terms of throughput, delay and jitter could be achieved. The performance metric for different scenarios are evaluated by the simulation experiments and analyzed numerically.

1.2. Organization of the Thesis

The thesis is organized into 8 chapters. The first chapter discusses the introductory elements, objective and motivation of the research work. Chapter 2 introduces the Wireless local area network and 802.11 protocols. It also explores the PHY and MAC layer architecture of 802.11. Chapter 3 covers the basic of Mesh networking, 802.11s, its challenges and extended service set. Chapter 4 presents the necessity of channel assignment in Mesh network and the previous work done on this issue. Chapter 5 introduces the problem statement and the architecture of our Mesh network. Chapter 6 explores elaborately the channel allocation strategy in our Mesh network. It also discusses how the total area is gradually divided between two channels and the corresponding experimented scenarios. Chapter 7 examines the performance of the Mesh in case of two orthogonal channels by extensive simulation study with NS2. The performance is analyzed numerically. Conclusion is drawn in Chapter 8.

2. WIRELESS LAN

Wireless Local Area network or WLAN is an autonomous system of static or mobile routers (and associated hosts) connected by wireless links. Their union forms an arbitrary graph. The routers can move randomly and can organize themselves arbitrarily; thus, the wireless topology might change rapidly and unpredictably. Such network may operate in a standalone fashion, or may be connected with a larger Internet. Each node participating in a network could act as both host and router. The nodes in WLAN can consist of desktop, laptops, pocket PC, personal digital assistants etc. These conventional nodes are very limited in resources such as CPU capacity, battery power and bandwidth. Both routers and nodes consist of a wireless transceiver equipped with a suitable antenna. The antenna may be omni-directional (broadcast), highly-directional (point-to-point), possibly steerable or some combination of them.

2.1. 802.11 Standards and its Amendments

802.11 is an evolving family of standard developed for 5 and 2.4 GHz public spectrum bands for wireless local area network communication by IEEE standard committee.

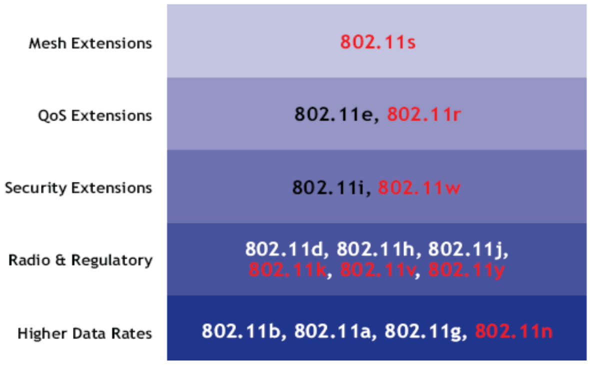

Figure 2.1. The enhancement of basic 802.11 standards. The red colored amendments are not yet approved. (Troops 2005)

The original standard of 802.11 was first approved in 1997 by IEEE standard committee. In order to expand the applicability of 802.11, a number of amendments to the original version have been approved since 1997 by IEEE. A lot of factors such as higher bit-rate, better QoS, more security and broader applicability mainly played the vital role behind these modifications of MAC and PHY layer. 802.11b (2.4 GHz) was the first broadly accepted standard followed by 802.11g and 802.11n. 802.11a uses 5GHz band with 8 non-overlapping channels. The evolution of basic 802.11 amendments is summarized in Figure 2.1 above.

The enhancement to the 802.11 standards are addressing and enabling new markets, new applications and new scenarios. These developments will continue to drive adoption and further investment leading to the further growth and maturity of the standard. (Troops 2003)

2.2. Physical Layer (PHY)

The 802.11 physical layers operate in 2.4GHz and 5GHz ISM band. The significant advancement in microwave and RF circuit design leads to the efficient and effective deployment of high-speed wireless radio in 802.11. The original 802.11 possesses data rate of 1 Mbps and 2 Mbps. Two spread spectrum technique, Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) were used in the first version. In order to cope with various type of fading as well as to increase the data rate to a usable level, the orthogonal frequency division multiplexing (OFDM) has

Table 2.1. 802.11 a/b/g/n Standards at a glance.

	802.11a	**802.11b**	**802.11g**	**802.11n**
Standard Approved	July 1999	July 1999	July 2003	Not yet ratified
Maximum Data rate	54 Mbps	11 Mbps	54Mbps	600Mbps
Modulation	OFDM	DSSS or CCK	DSSS or CCK or OFDM	DSSS or CCK or OFDM
RF Band	5 GHz	2.4 GHZ	2.4 GHZ	2.4 GHZ or 5 GHz
Channel Width	20MHz	20 MHz	20 MHz	20 Mhz or 40 MHz

been later introduced in 802.11 physical layer technologies. The modulation techniques together with adaptive link control have increased the theoretical bit rate from 1 Mbps to 54Mbps. Besides this, the adaptive antenna system and antenna diversity are now a momentous research area in physical layer technology. The various amendments of 802.11 and the corresponding modulation technique, bit rate and channel width are given in table 1 above.

2.2.1. PHY Sublayers

The physical layer of 802.11 is divided into two sublayers, the Physical Layer Convergence Protocol (PLCP) and Physical Medium Dependent (PMD) sublayer. As shown in Figure 2.2, MAC layer pushes the MAC Protocol Data Unit (MPDU) to the PLCP sublayer. After an addition of a preamble and a header the PLCP protocol data unit (PMDU) is sent to the PMD sublayer. The PMD sublayer directly interfaces the wireless medium and performs necessary modulation and demodulation action.

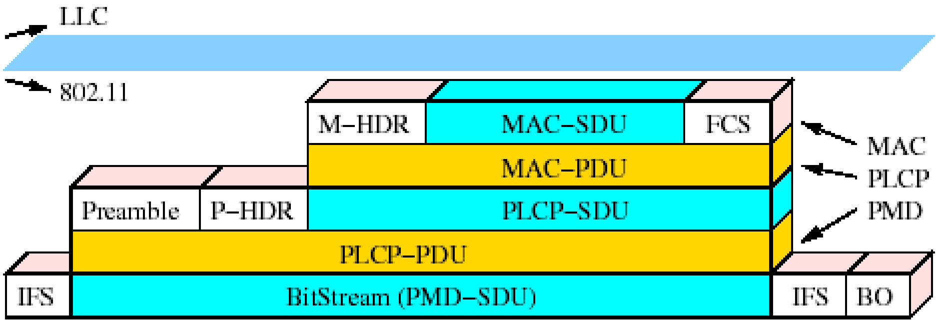

Figure 2.2. Overhead at different sublayers in IEEE 802.11. (Jangun 2003)

The PMD is responsible for the transmission and reception of PMDU through wireless medium. The construction of a PLCP frame for FHSS defined in IEEE 802.11 (R2003) is shown in Figure 2.3. The size and function of the preamble and header varies to some extent from one 802.11 standard to another.

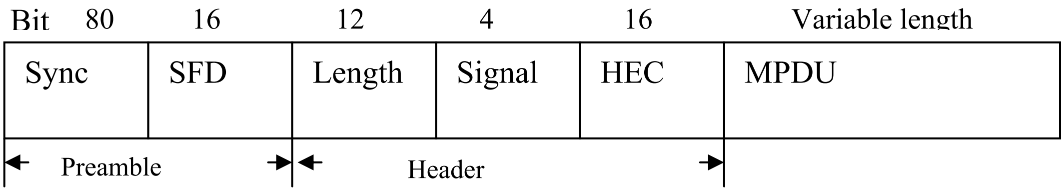

Figure 2.3. The PLCP frame format.

The Sync field consists of a string of alternating zero-one. Its purpose is to synchronize the transmitter and the receiver. The Start Frame Delimiter (SFD) mainly defines the beginning of a frame. The length field contains the number of byte contained in MPDU. Its valid values are 1 to 4095. The Signaling field contains the modulation scheme (data rate) to be used for the MPDU. However, it can be mentioned that the transmission speed of MPDU is different from the transmission speed of preamble and header of the same frame. Each 802.11 a/b/g has their own basic rate to transmit the preamble and header. The basic rate varies from 1 Mbps to 6 Mbps according to the 802.11 version. The Header Error Correction (HEC) is a CRC-16 error detection field.

2.2.2. 802.11 Modulation Scheme

Basically the goal of the modulation technique is to efficiently accommodate more bits per symbol as well as to reduce the signal to noise ratio during transmission. In a wireless network all nodes transmit through a common air medium. Therefore the signals here are mostly affected by noise and interference coming from neighboring nodes. The quality of the signal further deteriorates drastically by fading. Hence a suitable modulation technique should be adopted to cope with these adverse phenomenons.

In the first 802.11 standard, Frequency Hoping Spread Spectrum (FHSS) technique was used. In FHSS, a node changes its carrier frequency randomly during transmission of a data packet. The carriers are chosen from a set of frequency in a given band. As the signal is spreaded in the frequency domain, they are less affected by noise and interference. Although the offered data rate of FHSS is 2Mbps, indeed it is not a satisfactory figure.

In 802.11b standard, Direct Sequence Spread Spectrum (DSSS) is used as a modulation technique. In this method the data stream are multiplied by a set of chip. The chips are narrow-width bit stream and are orthogonal to each other. A pulse narrower in width has a significant frequency distribution. Hence the multiplication of data stream with the narrow width chip set expands the bandwidth of data in frequency domain. This spreading technique has achieved the transmission data rate up to 11 Mbps.

In Orthogonal Frequency Division Multiplexing (OFDM) used in 802.11a, the available band is divided into a many narrow band orthogonal sub channel. Each sub channel is used to transmit data. The OFDM is very stable against multipath fading. The theoretical data rate of 802.11a is around 54Mbps.

2.2.3. Antenna and Transmission Power

Both transmitter and receiver in WLAN are interfaced with the common propagation medium by a suitable antenna. The modulated signal is transmitted through the medium by an antenna. The commonly used antenna for a wireless node is omni directional that radiates power uniformly in one plane with a directive pattern shape in a perpendicular plane. The Effective Radiated Power (ERP) of an antenna is a very crucial factor while tuning the network performance. The more radiated power causes more exposed area for a node. This in turn produces more MAC contention and interference to other nodes and deteriorates network performance.

On the other hand, small radiated power causes weak SINR as well as hidden and exposed node problem. In order to have optimum response from a WLAN the antenna gain and ERP need to be optimized. In our work the ERP is optimized by using a network designing software tool called Site Designer (DACI 1990) before simulation.

Besides Omni directional antenna, other types of highly directive antennas are used in wireless nodes to reduce the exposed area. In this case the routing protocol needs to be aware of its directivity. For further increase of capacity and to mitigate the problem caused by the fading, delay spreading and co channel interference, multiple and smart antenna systems are now gaining much popularity.

2.3. 802.11 Medium Access Control (MAC)

In order to access the medium, 802.11 MAC layer uses Carrier Sense Multiple Access with Collision Avoidance or CSMA/CA technique. In this purpose 802.11 uses two kind of function, one is Distributed Coordination Function (DCF) and another is Point Coordination Function or PCF. Later a priority based access technique is introduced in 802.11e for time sensitive data such as voice and video. The access mechanism of each of the above method is described briefly in the following subsections.

2.3.1. The Distributed Coordination Function (DCF)

The distributed coordination function (DCF) is predominantly used in the access method of 802.11. It is an automatic medium sharing mechanism by using CSMA/CA among 802.11 compatible PHYs. Two types of carrier sensing method are used in sensing the medium, one is physical sensing and another is virtual sensing. The physical carrier sensing mechanism is provided by the physical layer and the virtual carrier sensing is provided by the MAC layer. As shown in Figure 2.4 when a station wants to transmit, it first senses the medium for a time slot called Distributed Inter Frame Space (DIFS). If the medium is not determined to be busy the station stars to send data packet. After successful reception, the receiver sends an ACK signal to the station. A time slot called Short Inter Frame Space (SIFS) is followed by the ACK signal.

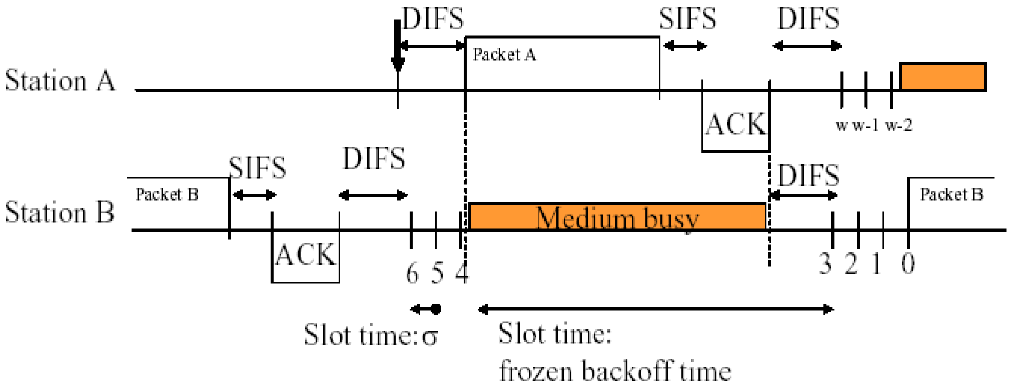

Figure 2.4. The basic IEEE802.11 access technique. (Jäntti 2006)

However, if the medium is sensed busy, a station will wait till the medium is sensed free. When the medium is detected free, the station will transmit if the medium remains free after a DIFS followed by some randomly chosen back off time slots. The reason of introducing random backoff slot after DIFS is to reduce the probability of collision after a successful transmission in the medium. Because during a transmission phase, the medium remains occupied by a single node and as soon as the medium is released by the transmitting node, a potential number of nodes compete to access the medium simultaneously. In this contest the node who will randomly choose the smallest number of backoff slots will win in the long run.

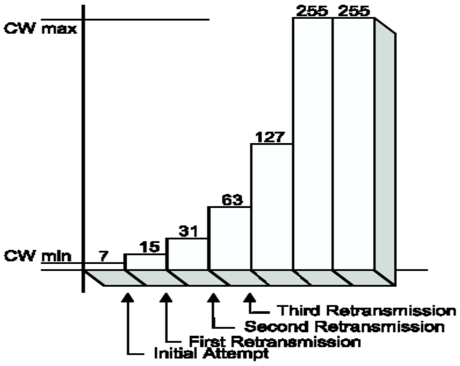

Figure 2.5. The Exponential increase of CW for unsuccessful attempts. (IEEE 1999)

The slot size is equal to the time needed to sense the medium effectively. The backoff time slots are uniformly chosen from a contention window [CW_{min}, CW_{max}] maintained by each node. The size of the contention window is adjusted according to the number of collision the node experiences. At first transmission attempt the window parameter CW is set to CW_{min}. Later for each collision experienced by the node the CW is incremented exponentially (2^i) up to CW_{max}. The incremental process of CW is shown in Figure 2.5. The CW will remain at the value of CW_{max} until it is reset. The CW will be reset to CW_{min} gradually when the node detects the medium idle while taking a transmission attempt.

In order to mitigate the problem caused by the hidden and exposed node, Request to Send (RTS) and Clear to Send (CTS) handshaking mechanism is incorporated in basic DCF technique. RTS-CTS access method in basic DCF is shown in Figure 2.6.

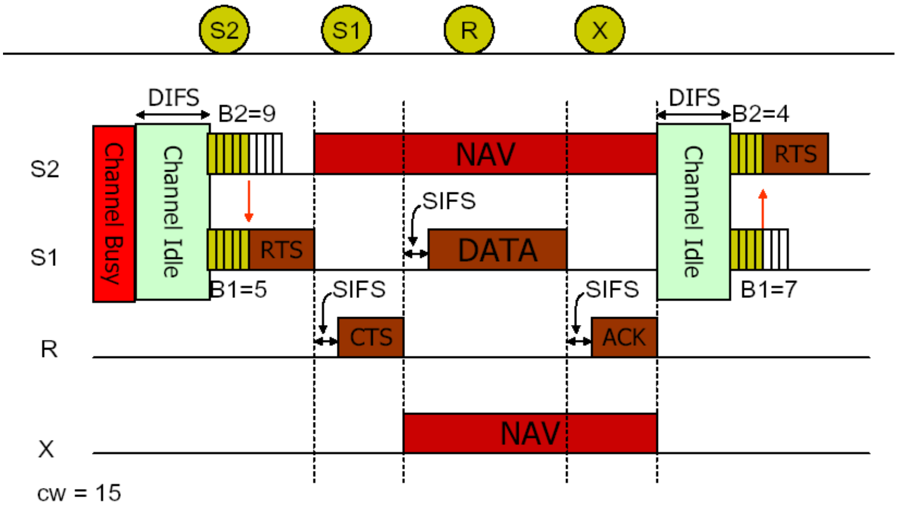

Figure 2.6. Access mechanism with RTS/CTS in 802.11 MAC. (Mohapatra 2006)

Any node overhearing the RTS or CTS will stop its transmission for a period defined in its network allocation vector or NAV. The duration of the transmission is provided by the RTS/CTS frame. Each node keeps this value in its network allocation vector (NAV). This type of sensing is called virtual carrier sensing.

2.3.2. The Point Coordination Function (PCF)

The 802.11 PCF, in contrast to DCF, is a centralized access mechanism. The access point polls the stations to transmit.

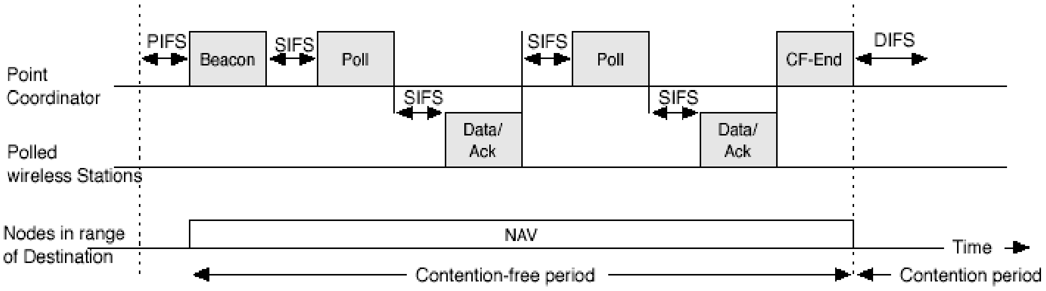

Figure 2.7. The PCF Access mechanism. (Zauner 2006)

No station is allowed to transmit unless it is polled by the access point. As shown in Figure 2.7 when a station is polled by the access point, the station in response starts transmission to the access point. As PCF give every station a turn to transmit, a maximum latency is guaranteed. But the main drawback is, it is not scalable enough. Time bounded data such as voice and video can be effectively transmitted by PCF mechanism.

2.3.3. EDCF and HCF

In order to provide QoS for the time sensitive application, an enhanced medium access technique has been proposed by Task group TGe in 2005. In 802.11e the medium access technique has two functions, one is Enhanced Distributed Coordination Function (EDCF) and another is Hybrid Coordination Function (HCF). In 802.11e access mechanism, priority is imposed to the traffic. Traffic with highest priority will get precedence to access the medium. EDCF is the contention based enhanced version of DCF, supporting the QoS.

Table 2.2. Recommended values for AIFS and CW.

AC	AIFS	CWmin	CWmax
0 (Best effort)	2	31	1023
1 (video probe)	1	31	1023
2 (video)	1	31	63
3 (voice)	1	7	15

Instead of treating all traffic with a single DIFS value and a single (CW_{min}, CW_{max}) set, EDCF defines that the channel access has up to four Access Categories (AC), each with its own Defer Time called Arbitrary Distributed InterFrame Space (AIFS) and CW_{min}/CW_{max} values (Dajiang 2003). The list of AIFS and CW is given in Table 2.2 above. HCF on the other hand is not a contention based access technique like EDCF. Under HCF, a Hybrid Controller (HC) polls STAs to transmit, assigning them a Transmission Opportunity (TXOP) defining a duration for which the STA may send data (Cowling 2004).

2.3.4. MAC Frame Formats

Each MAC frame consists of three parts, a MAC header, a Frame body and a Frame Check Sequence (FCS) as shown in Figure 2.8.

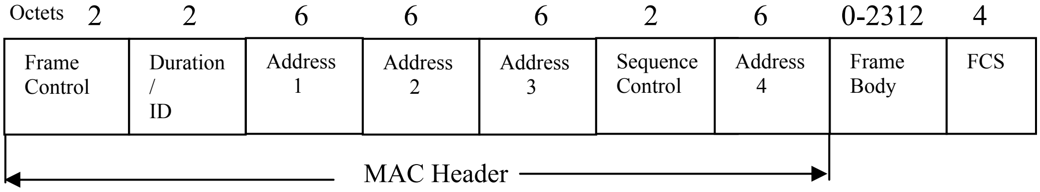

Figure 2.8. The IEEE 802.11 MAC frame structure.

The header comprises Frame control, Duration/ID, Addresses and Sequence control. The Frame Body contains MSDU and the FCS contains 32 bit cyclic redundancy code (CRC-32). It is calculated over all the field of MAC header and Frame Body. A polynomial of degree 32 is used in this error detecting code.

The Frame Control field mainly keeps the information regarding protocol version, type, power management, retry, fragmentation, privacy, order etc. The Duration/ID field carries the information of ID and duration. The duration value is used by NAV in virtual sensing method. The Address Fields carry the information about basic service set identifier, destination address, source address, receiver address and transmitter address. The Sequence Control field keeps the information of sequence number and fragment number of the total frame.

The RTS, CTS and the ACK are the main control frames in 802.11 MAC to transmit the data frame successfully. The Request to Send (RTS) frame format is shown in Figure 2.9a. The Frame Control field keeps the same kind of subfields like before. The Duration value is the time in microsecond required to transmit data to the receiver plus one ACK frame plus one CTS frame plus three SIFS interval. The RA and TA keep the address value of the receiving station and transmitting station respectively. The FCS is used for CRC.

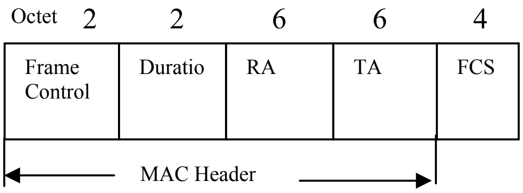

Figure 2.9a. The IEEE 802.11 RTS frame structure.

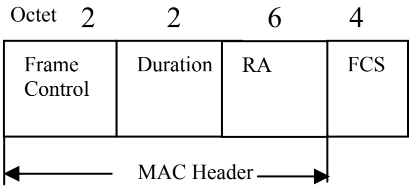

Figure 2.9b. The IEEE 802.11 CTS frame structure.

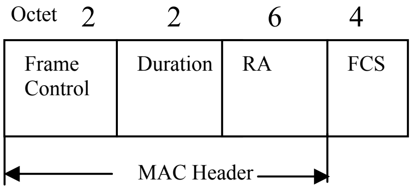

Figure 2.9c. The IEEE 802.11 ACK frame structure.

Figure 2.9. The structure of the basic MAC control frames.

In CTS frame shown in Figure 2.9b the RA is copied from the TA field of the immediately received RTS frame. The Duration value is determined from the duration field of the previous RTS frame minus the time to transmit a CTS frame and a SIFS. FCS is used for CRC.

In ACK frame shown in Figure 2.9c the RA value is copied from the address 2 field of the previous data frame. If the more fragment bit is set to 0 in the previous data frame the duration field of the ACK is set to 0. Other wise the Duration value is the value obtained from the Duration field of the previous data frame minus the time in microsecond required to transmit an ACK and a SIFS.

2.4. IEEE 802.11 Performance

Before discussing the performance factors of a multihop 802.11 LAN in general, we shall try to explore the role of the PDU size, the header size and the control signal over its throughput. In this purpose, the sequence of events in case of a successful transmission is shown in Figure 2.10 below. The total time in a successful transmission in 802.11 basic access technique is the addition of transmission time of the PDU plus the necessary time required for the control signal. Thus from Figure 2.10, total time in basic access, $T_{Basic}=T_{data}+T_{SIFS}+T_{ACK}+T_{DIFS}+T_{Backoff}$. Similarly for RTS-CTS technique total time, $T_{RTS\text{-}CTS}=T_{RTS}+T_{SIFS}+T_{CTS}+T_{SIFS}+T_{data}+T_{SIFS}+T_{ACK}+T_{DIFS}+T_{Backoff}$.

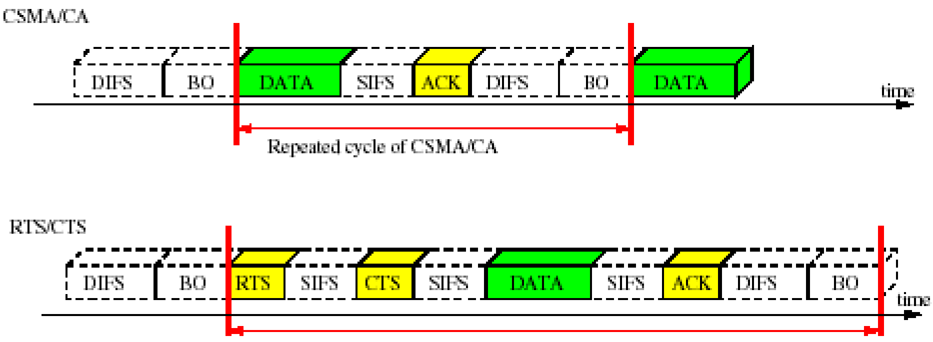

Figure 2.10. The transmission frame structure in a successful transmission. (Jangun 2003)

The Theoretical Maximum Throughput (TMT) is evaluated by Jangun et al. (2003:249-256). The paper calculated the TMT of the MAC layer under some basic assumptions such as, the bit error is zero, there is no MAC contention, no packet loss, no MAC fragmentation and the sending node has always packet ready to transmit. Under this above condition the Theoretical Maximum Throughput (TMT) of the MAC is the ratio between MSDU size and the total time to send the MSDU successfully.

$$\therefore TMT = \frac{MSDU\ size}{Total\ time\ required\ to\, send\ MSDU}$$

Hence in case of RTS-CTS mechanism

$$TMT = \frac{MSDU\ size}{T_{RTS-CTS} = T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS} + T_{ACK} + T_{BO} + T_{DATA}}$$

As there is no Mac contention in the assumption, there is no increase of contention window during transmission. Thus the expected value of backoff window CW will be $CW_{min}/2$. The value of each term of the denominator in TMT expression depends on the modulation scheme declared by IEEE standard committee. As for example, in CSMA/CA OFDM-6, T_{RTS}=52µs, T_{SIFS}=27µs, T_{CTS}=44µs ,T_{ACK}=44µs, T_{DIFS} =34µs ,$T_{Backoff}$ =67.5µs.

Let determine the TMT for 1000 Byte MSDU under OFDM-6. After adding MAC header, FCS, Preamble and PLCP header (Figure 2.2), the time required to transmit only this data in OFDM-6 scheme is around 1400μs.

$$\therefore TMT = \frac{1000\,Byte}{34\mu s + 52\mu s + 27\mu s + 44\mu s + 44\mu s + 67.5\mu s + 1400\mu s} = 4.7\,Mbps$$

Therefore the PDU size makes a considerable impact on the theoretical maximum throughput. The impact of MSDU size on maximum throughput for various modulation schemes is depicted in Figure 2.11.

The PDU size is application specific and apart from the PDU, the performance of 802.11 depends mainly on network topology, node density, number of channels used per node, traffic pattern, transmission power and node mobility.

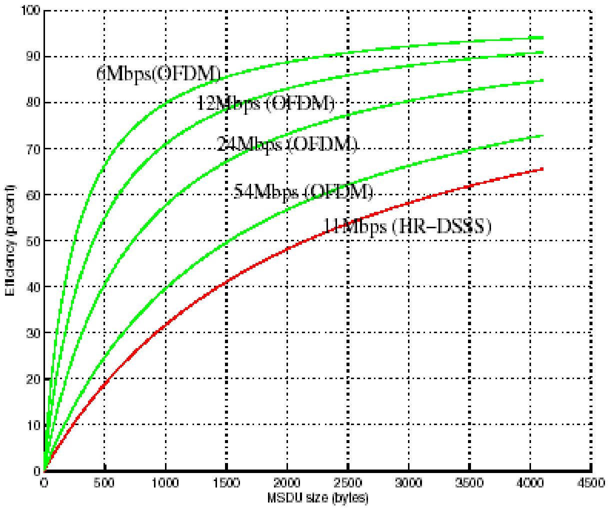

Figure 2.11. MSDU packet size versus the percentage of maximum capacity. (Jangun 2003)

For multi-hop networking, it is well known that communication protocols suffer from scalability issues (Huang 2002; Jain 2005), i.e., when the size of network increases, the network performance degrades significantly. For a multi-hop network the throughput decreases rapidly as the number of hop increase. In case of TCP, this property seems very significant as the reliability falls due to the increasing number of hop.

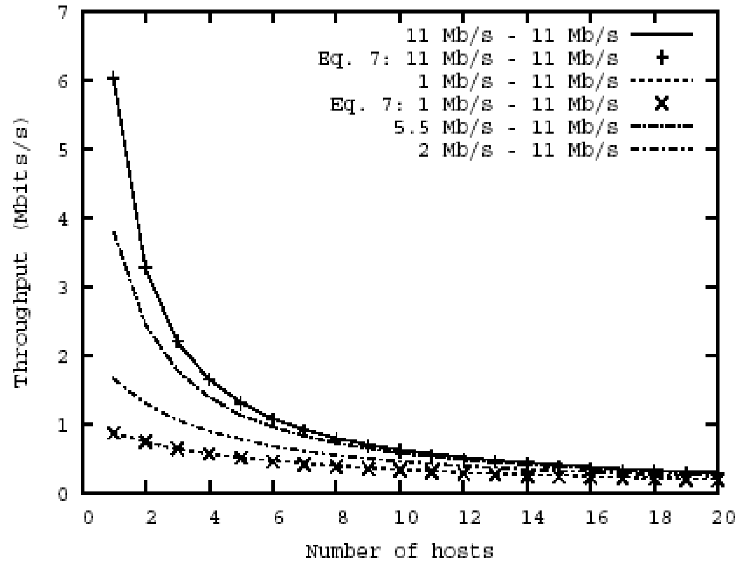

Figure 2.12. Throughput experienced by an 802.11b host when all hosts except one transmit at 11Mb/s. (Heusse 2003)

The node intensity influences the network performance drastically. Since all nodes share a common medium in wireless network the MAC contention increases as the number of node increase. Gupta et al. (2002:279-304) observed that the amount of throughput is related to the node by $n^{-1.08}$, where n is the number of node in the network. The relation between number of node and the throughput is shown in Figure 2.12.

The throughput also depends on the packet size. The small size packet offers much overhead than that of big size packet during transmission. It is shown before that the efficiency depends on the MSDU Packet size. The Figure 2.11 above depicts the MSDU packet size versus the efficiency. The efficiency is measured by the percentage of theoretical maximum throughput achieved.

The transmission power is also a very considerable factor in performance. Less transmission power may cause hidden node and exposed node problem. On the other hand, more transmission power will create more exposed area for a node, results MAC contention. Hence transmission power should be optimized to have better performance.

3. WIRELESS MESH NETWORK

Wireless Mesh Networking is an emerging area of interest in recent wireless technology. It is a promising technology in providing inexpensive and rapidly deployable network structure. This multihop wireless entity although works well with current 802.11 standards, there are lot of challenges remained to be solved to make WMN efficient and scalable enough. Wireless Mesh is a multihop wireless network having the property of self-healing and self-forming. Researchers all over the world are working to have an efficient protocol standard for this promising multihop network structure. The basic features of WMN, its application areas, challenges, and the proposed extended service sets are discussed in this chapter.

3.1. The Basic of Mesh Network

The architecture of the basic multihop mesh network and the pros and cons of using IEEE 802.11 in this multihop technique is explored in the following subsections.

3.1.1. Architecture

As shown in Figure 3.1 below, a Wireless Mesh Network (WMN) is comprised of Mesh Points (MPs), Mesh Access Points (MAPs) and a Mesh Point Portal (MPP). MPs act as a router and MAPs act as an access points in addition to MP’s functionality. Besides routing functionality the MPP is equipped with gateway facilities for connecting to an external network. A Mesh node forwards packets for other nodes that might not be with in direct wireless transmission range of their destination. The mesh node can configure itself automatically and are able to reconfigure dynamically to maintain the mesh connectivity. This gives the mesh its self-forming and self-healing properties. This self–sufficient relationship among the mesh nodes eliminates the necessity for centralized supervision. This characteristic also offers many plus points to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage (Akyildiz 2005:445-487).

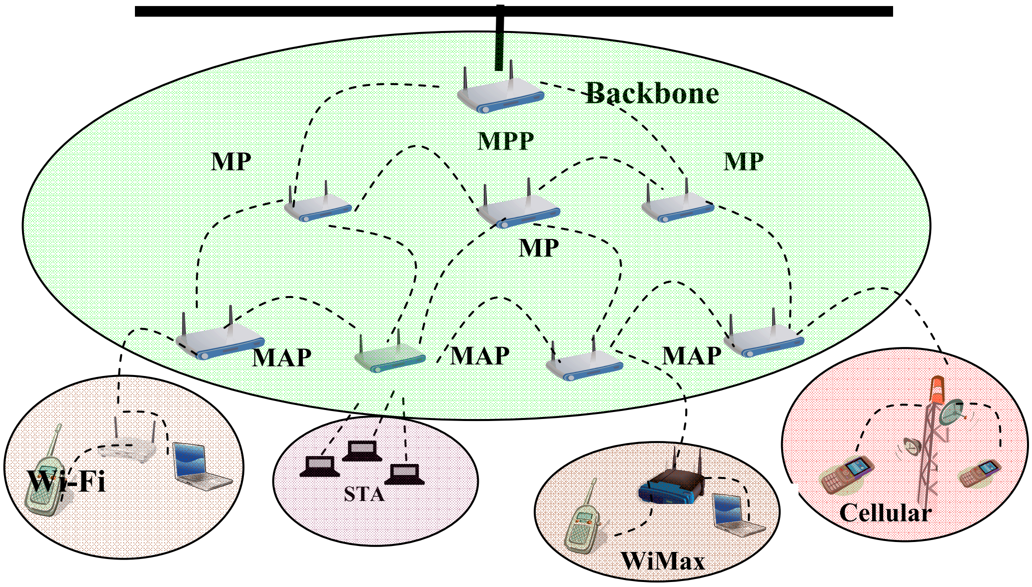

Figure 3.1. Basic Infrastructure of a Wireless Mesh Network.

Traditional Stations (STA) such as desktops, laptops, PDAs, PocketPCs, phones having wireless network interface cards (NIC) can connect directly to wireless MAP. WMNs help the users to be always-on-line anywhere and at any time. Moreover the gateway/bridge functionalities in mesh routers enables the integration of WMNs with various existing wireless networks such as cellular, wireless sensor, Wireless-fidelity (Wi-Fi), worldwide inter-operability for microwave access (WiMax), Wimedia networks etc. (Akyildiz 2005:445-487).

3.1.2. Routing in Mesh network

The routing strategy of wireless mesh network is totally different from wired LAN and cellular network. However, as the mesh consists of some common features of adhoc wireless network, the routing protocol of adhoc network is also applicable to mesh network in some extent. As for example, the Microsoft mesh network (Microsoft) is using Dynamic Source Routing (DSR) protocol, Firetide networks (Firetide) are using Topology Broadcast Reverse Path Forwarding (TBRPF) protocol and many companies (Kiyon) are using Adhoc On-Demand Distant Vector Routing (AODV) protocol in their mesh backbone. Although the routing protocol of adhoc network runs in mesh network up to a certain limit, there are some basic differences between adhoc and mesh network.

Mesh networks are inherently multihop in structure and their access points are static in nature, thus power consumption is not a primary concern for the mesh backbone. But in case of adhoc network, mobility and power consumption are very important issue. The client of the mesh may be static or mobile, thus the adhoc routing protocol may work fine only for the mesh clients. But for the entire mesh network, special attention should be given for both backbone and the clients while selecting the right protocol.

There are lots of things to do with the mesh routing protocols. First of all, the recent routing protocols are not scalable enough to fulfill the requirement of a multihop mesh backbone. In order to get satisfactory performance from the mesh, scalability should be the primary concern. Besides this, the conventional adhoc routing protocol treats the MAC as a transparent layer and are only aware of the network layer. In this context, a cross layer designing can be a very promising effort to improve the efficiency. Also a new set of performance metric should be defined and have to be taken care in the routing protocol. As for example, minimum hop count can not be a good measurement unit while determining a good routing path in a mesh network. Because, a route having minimum hop does not necessarily mean a high capacity route. Hence a new type of performance metric should be considered. Currently expected transmission count (ETX), per hop round trip time (RTT) and per hop packet pair metric are proposed in Link Quality Source Routing (LQSR) protocol. The LQSR is a modified version of DSR. In our research work we selected the route on the basis of Expected Transmission Time (ETT). In this method a source node will choose the route for which the transmission time of a packet from source to destination is minimum. Other criteria that are expected form the mesh routing protocol is its awareness for load balancing and link failure while in operation. At present these above properties are absent from the current adhoc routing protocol and must be to be integrated to have a satisfactory response from a multihop network.

3.1.3. TCP Performance in 802.11 Multihop Mesh

The Transmission control protocol (TCP) is a connection oriented transport layer protocol that provides reliable end to end data service. Although the TCP with its slow starting property works fine in a wired network, its performance drops considerably in an 802.11 based multihop wireless LAN.

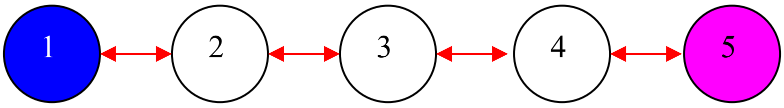

Figure 3.2. The 4 hop simulation scenario. Node 1 acts as TCP source and node 5 acts as a TCP sink.

There are two common flaws of TCP over 802.11 multihop network, one is unstable throughput and another is unfair flow. Shugong Xu et al. (2001:130-137) studied the performance of TCP in a multihop wireless network. They arranged the nodes like a string to form a multihop structure as shown in Figure 3.2 above.

In the above setup, node 1 contains the traffic source and node 5 acts as a sink node. The TCP packet size is 1460 Byte. Nodes are placed 200 m apart. Reno TCP is used in this simulation as it has fast recovery property when compared to others.

The simulation was run for 120 second for different window size. The achieved throughput for different window size is shown in Figure 3.3. The throughput is measured over each 1 second interval. As shown in Figure 3.3a and 3.3b, the TCP throughput is fluctuating between zero and a maximum value throughout the simulation period. The reason of this oscillation is the collision of data packet between different hop. Due to the collision, some of the intermediate node cannot reach the adjacent node at all. After trying for maximum retry limit which is seven in 802.11MAC, the node stops, drops the queued packet and reports route failure to the source. This will trigger the source node to find and establish a new route. After setting up a new route, the source will again start to transmit. This frequent route failure and route finding event during transmission creates instability. Basically, the collision with the exposed station prevents an intermediate node to send its data packet to the adjacent node. The more will be the probability of collision the more serious will be the problem.

The small window size of TCP may help to improve this hazard, because the small window size will disallow the nodes to push more data packet at a time without acknowledgement. This will in turn reduce the probability of MAC contention in the medium and hence will reduce the probability of intermediate link failure. In Figure 3.3c, when the window size is set to 4 the throughput become more stable than before.

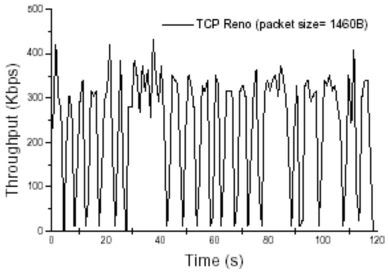

Figure 3.3a. Throughput for window=32

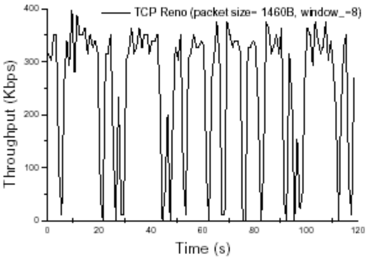

Figure 3.3b. Throughput for window=8

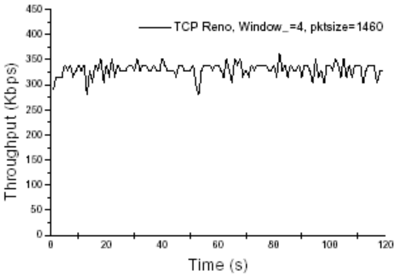

Figure 3.3b. Throughput for window=4

Figure 3.3. The oscillating TCP throughput in a multihop wireless network. The distance between the source and the sink is 4 hops. The average is taken over 1 second interval. (Shugong 2001)

Another flaw of TCP in a multihop wireless network is the unfairness among different flows. Raniwala et al. (2007:2361-2365) discussed three major unfairness issues of this kind. Figure 3.4 depicts those fairness problems in a multihop network. The node getting less fairness is marked as red and the node getting more fairness is marked as green. The dominant flows are indicated by continuous line and the weak flows are indicated by dotted line.

In Figure 3.4a node 2 is in the sensing range of node 3 but node1 is not aware of the transmission attempt of node 3 as it is situated out of its sensing range. Although the RTS/CTS mechanism stops a hidden node from interfering an ongoing transfer, it cannot prevent the hidden node 3 from initiating of RTS/CTS in an inopportune time. As a result node 1 backs off. TCP further amplifies this problem by triggering its congestion control mechanism unnecessarily. This gives opportunity to node 4 to transmit in the idle time. However, the repeated unsuccessful attempts to transmit, enforces node1 to increase its contention window rapidly. On the other hand, the ongoing success of transmission leads to a small window size for node 4. Thus in the long run, the flow F1 is suppressed by the flow F2. RTT based unfairness is shown in

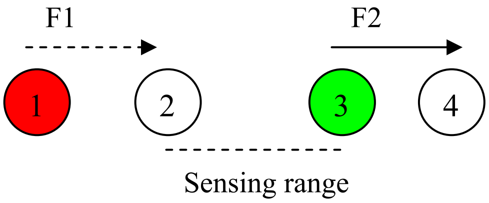

Figure 3.4a. Unfairness due to hidden node problem.

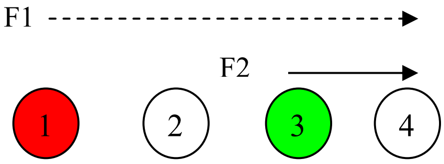

Figure 3.4b. Unfairness due to large RTT

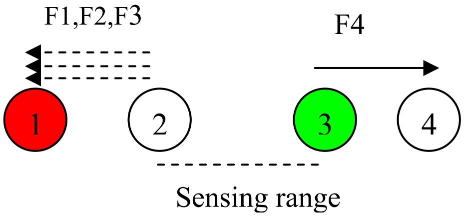

Figure 3.4c. Unfair channel sharing due to multiple flows

Figure 3.4. Common fairness problems in TCP in 802.11 multihop networks.

Figure 3.4b, where flow F1 traverses more hop than flow F2. As the RTT of F1 is greater than F2, TCP gives more bandwidth to F2. In Figure 3.4c flows F1, F2, F3, F4 are sharing the same channel. But the TCP protocol allocates more bandwidth to F4 than to others.

It is found that the inherent features of TCP for congestion control do not work well with multihop 802.11 MAC. TCP's ACK clocking does not work well with ACK bunching that occurs due to bursty medium access in different hop. Besides this, TCP is confused about the channel errors in a wireless network, a common property of multihop wireless network, with congestion related losses. As a result it switches its congestion control mechanism now and then. TCP is not RTT independent; the flow that has less RTT grabs the major portion of the common bandwidth. Hence a new service set is required to make TCP work smoothly in a contention based medium access control.

3.1.4. Application of Mesh Network

Mesh network can be employed in diverse applications. It can be used to build broadband home networks, to extend the coverage area of enterprise WLAN networks, to build automation and to construct ad hoc networks etc. Basically its versatile applications and outstanding performance leads to the tremendous research activities with mesh network. There are many applications that cannot be put into practice by using cellular networks, WiFi networks or even adhoc networks. It is found that in those types of applications mesh network can be the exact solution. Some application areas of mesh backbone are discussed by Ian F. Akyildiz et al. (2005:445-487). Those areas are described briefly below.

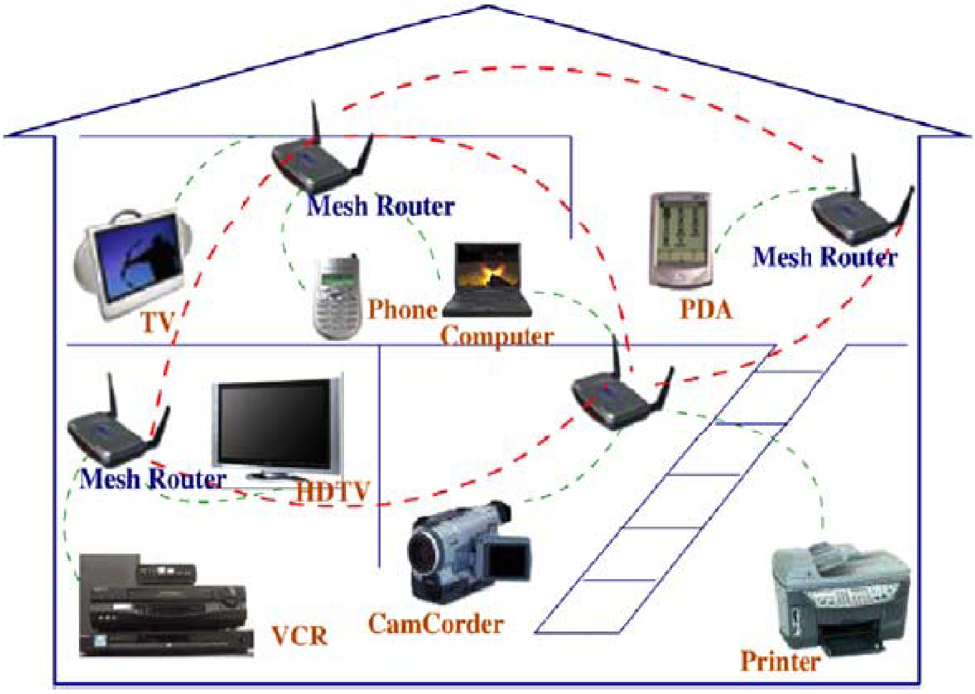

Figure 3.5. A Broadband Home Networ. (Akyildiz 2005:445-487)

- Broadband Home network. The main problem in home networking is to find out the proper location for the placement of access points, because a home consists of many dead zones. In order to find the suitable locations for the access points it requires a site survey. The survey in turn adds a big amount of cost. In that case, extra access points are generally deployed to cope with the dead zones. As the cabling cost from the hub to each of the access point is expensive, the deployment of extra access point is always a non profitable choice for Ethernet. Again the WiFi network will not fit for this type of home application as there is not much scope of mutihop routing in WiFi network. In this context, a mesh network can eliminate those of the above problem very easily as shown in Figure 3.5. What we have to do is to simply replace the conventional access points by the Mesh access points. As the mesh access points are free from cabling problem and also free from any constraint for power consumption, the use of extra access point due to dead zone is not a big issue. Therefore in this type of application a wireless mesh network can be a very good choice.

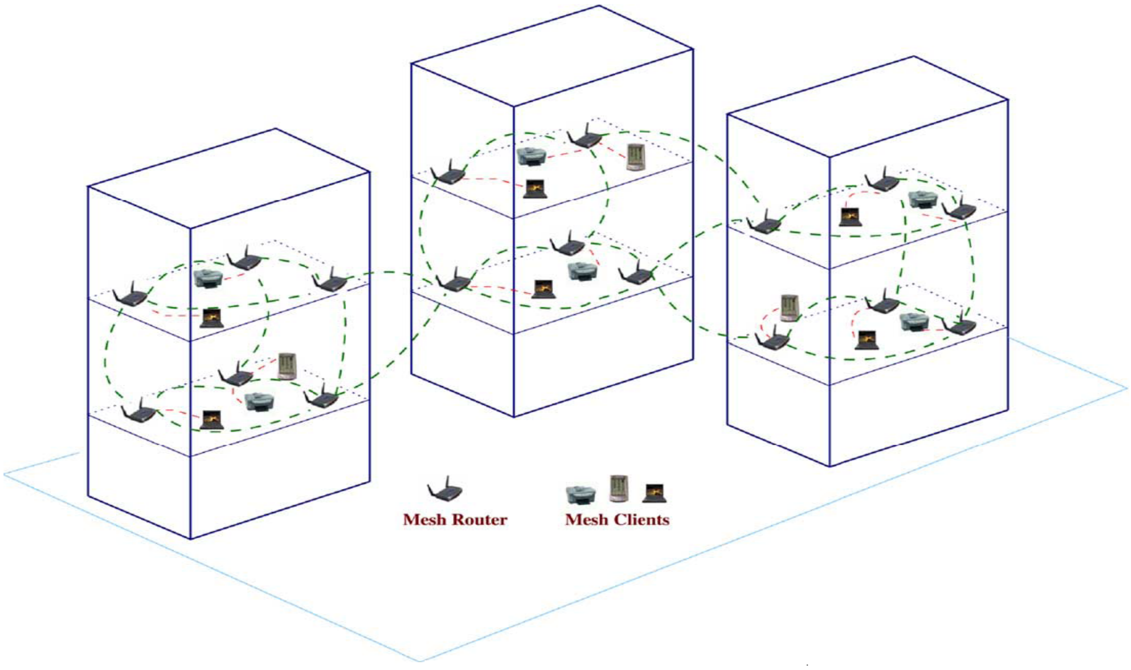

Figure 3.6. An Enterprise Network. (Akyildiz 2005:445-487)

▪ Enterprise Network. An enterprise network is a medium size network within an office or a large network connecting multiple office buildings. While using the conventional 802.11 WLAN each office acts as a separate island and it requires Ethernet cable to integrate those networks together. Obviously it is too much costly and prone to link failure. If the access points are replaced by the mesh routers as shown in Figure 3.6, the robustness, congestion problem as well as the capacity of the network can be improved significantly. The enterprise network can be used in airport, in multiple office building, hotels, sports centre etc.

- Metropolitan Area Network. As the network area expands, the necessity of wireless mesh Network becomes inevitable. Because it is difficult to cover the vast network area with Ethernet or fiber optic cable. For this large and complex network the chances of link-failure are higher and the suitable placement of access point is also difficult, therefore the network in turn looses its robustness and reliability. However, as the throughput of the PHY layer has increased to 54 Mbps the mesh network can be a precise solution of this kind of application. A mesh with proper allocation of channel can offer robust and reliable broadband service in metropolitan area network as shown in Figure 3.7.

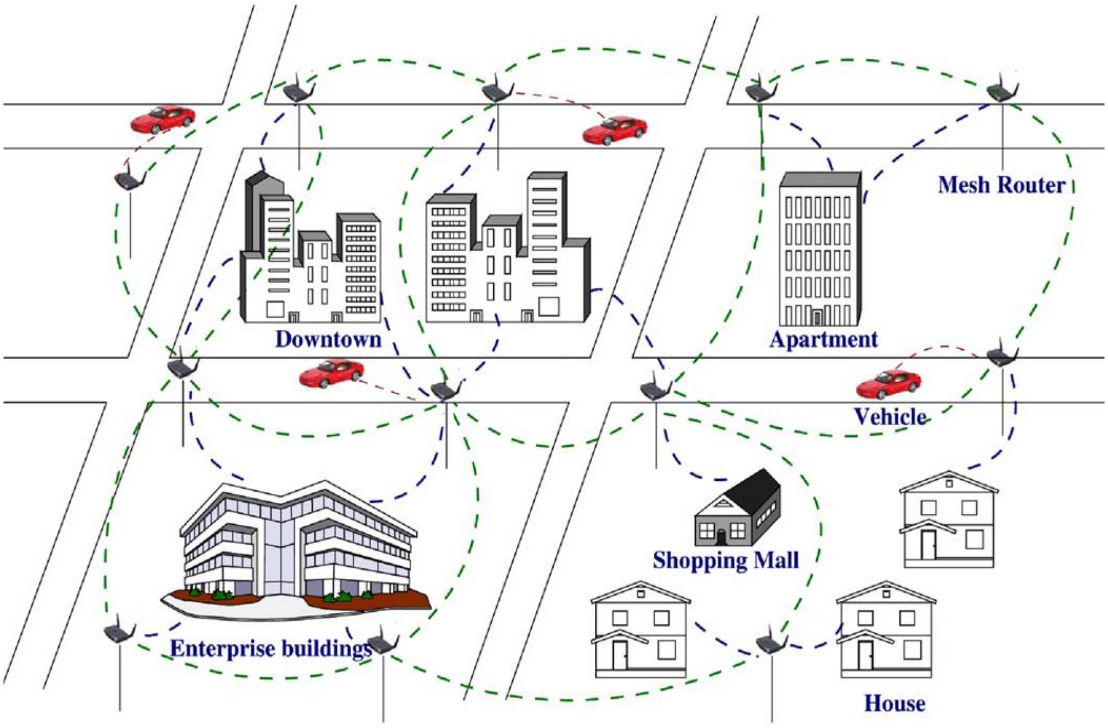

Figure 3.7. A Metropolitan Area Network. (Akyildiz 2005:445-487)

Apart from the above applications, Mesh network are providing reliable and satisfactory service in transportation system, building automation, health and medical system, security surveillance etc. As all the necessary components are already available in the form of ad hoc routing protocols, IEEE 802.11 MAC and PHY layer protocol, wired equivalent privacy security etc., installing a Wireless Mesh Network is not a difficult task. Many companies have already taken into account the bright prospect of this technology and are manufacturing WMN product.

However, the multi-hop wireless networks are not trouble free at all. In order to make the WMN efficient and scalable enough, considerable research efforts are still needed.

3.2. IEEE 802.11s Extended Service Set

The IEEE 802.11 was proposed mainly for a single hop adhoc wireless structure. The aspects of using IEEE 802.11 in a multihop wireless network are explored in the previous sections. It is clear that a new set of extend services is required to extract the full potential of the wireless mesh network. In the following two subsections the common challenges of Mesh network and the proposed extended service set are discussed briefly.

3.2.1. Challenges of IEEE 802.11 for Mesh

The conventional Ad hoc routing protocols as well as the medium access control technique are basically optimized for the single hop wireless network. Therefore they are not suitable for a multihop wireless mesh where high throughput, network security and fairness are the primary concern.

Some common problems of using IEEE 802.11 in a multihop network are discussed in section 3.1.2 and 3.1.3. In the current standard, the MAC and the network layer are transparent to each other. There is no coordination between them in case of mobility and network topology changing. As the Mesh networks have property of self healing and self-forming the MAC should be capable enough to reconfigure itself in changing environment dynamically. This necessitates the designing of cross-layer mechanism. Besides this, in order to enhance the throughput, the MAC should support transmission in multiple channels in each network node. The recent MAC does not provide this kind of facility. Network fairness is also a very big challenge for the mesh network. It is found that in a multihop network the nodes located at distant places from gateway are getting less facility than that of the near nodes. Thus the protocol should be efficient enough to take care of the network fairness. Unfortunately the adhoc wireless protocols don’t have this kind of facilities to prevent such spatial bias at present.

Security is also an important issue for the mesh backbone. As the backbone may support virtual private network (VPN) the security can become a primary concern in that case. It can be mentioned that there are some limited facilities of security in terms of authorization and authentication in wireless LAN, but they are not scalable enough to implement in commercial mesh network.

Though the power management is not a primary concern for the static mesh router, the mobile mesh client needs to be aware of it. Again in order to reduce the interference, transmission power is a very crucial factor. Reducing transmission power reduces interference. But in turn it may also introduce hidden node problems. Hence an efficient power management scheme should be incorporated in MAC and Network layer.

As a whole, in order to provide QoS, security, scalability and self healing ability to a wireless mesh, a modified of multihop wireless network protocol is indispensable.

3.2.2. Extended Service Set

Since the increasing demand of mesh network necessitates a new standard, a task group TGs was formed in 2004 to define the extended service set for mesh standard. The goal of this new standard is mainly to make the best use of capacity and time, to provide security for sensitive application, to conserve power for prolonged operation of mobile devices and to provide fairness by eliminating spatial bias, i.e.; all nodes irrespective of their location will get equal amount of facility. Hidenori Aoki et al. (2006) focused some of the fundamental functional blocks of the proposed IEEE 802.11s. The Figure 3.8 shows those basic components of 802.11s.

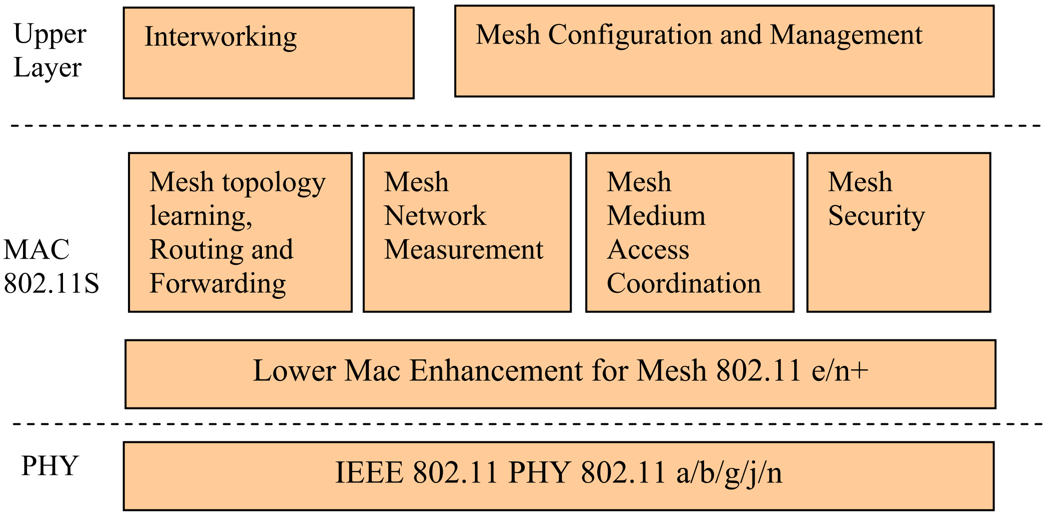

Figure 3.8. The basic architecture of 802.11s.

The Mesh topology learning, routing and forwarding block contains function of discovering neighboring node, function of getting routing metric and packet forwarding function. The measurement block performs the calculation of routing metric that are used by the routing protocol. The medium access coordinator block contains function to prevent degraded performance due to hidden and exposed node, function for performing priority control, admission control and function of spatial frequency reuse. The security block contains security function to protect data frame. It uses the WLAN security schemes defined in 802.11i. The interworking block contains the necessary function to integrate the wired LAN with the mesh backbone. It implements a transparent bridge between MPP and other IEEE 802 compatible network. The configuration and management block performs the operation of automatic setting of each MP's Radio Frequency (RF) parameter for Q_oS management. The RF parameters include frequency channel selection, transmission power etc.

In mesh network traffic mainly travel between gateway and stations. A hierarchical routing protocol is proposed in 802.11s amendment to exploit this logical tree based structure. The proposed Hybrid Wireless Mesh Protocol (HWMP) supports proactive hierarchical routing for mesh infrastructure as well as on demand routing for mobile devices. The on demand routing is based on AODV. Although HWMP is the default routing protocol, another optional routing protocol is proposed in draft standard. It is

Radio Aware Optimized Link State Routing or RA-OLSR where a group of node floods radio aware link metric and therefore reduce the control overhead.

Time synchronization and Enhanced Distributed Channel Access (EDCA) mechanism are the main features in MAC layer of 802.11s draft. By synchronization all the MP keeps a common mesh TSF time. It plays a critical role in beaconing functionality, especially in preventing beacon collision. In EDCA mechanism some property of NAV are enhanced by introducing full NAV, packet by packet NAV and NAV clearing mechanism. However the objective of this entire enhancement is to enable efficient allocation of mesh resources in respect of time and capacity. The proposed 802.11s MAC has also the ability to take care the congestion which is a common phenomena in a highly populated mesh network. The Efficient Mesh Security Architecture (EMSA) protects against unauthorized devices and malicious attacks.

However, the IEEE 802.11s standard has not been ratified yet. The task group TGs is going to meet in November 2008 to resolve the comments, improve its draft and go to letter ballot.

4. CHANNEL ASSIGNMENT IN MESH NETWORK

4.1 Introduction

Mesh routers are generally equipped with multiple network interface cards those operate in orthogonal channels. Therefore, the ultimate goal of the modern research activities is to efficiently utilize the available frequency channel space in 802.11 based wireless mesh network. Ability to utilize multiple channels with in the same network substantially increases the effective bandwidth available to the wireless nodes (Raniwala 2004:50-65). In our work, the routers that make the major backbone of the mesh were equipped with two 802.11 network interface card. A study was performed by varying the coverage area of the overlaid mesh network between two non-overlapping channels.

4.2. Necessity of Channel allocation

The recent explosion of 802.11 has made the wireless mesh as an inevitable network solution for industrial applications due to its high performance, low deployment cost, flexible operation and rugged architecture. However, as the stations deployed in a mesh network compete for the access of the same channel, the existence of co-located nodes degrades the network performance significantly. It is shown by Gupta et al. (2002:279-304) that the throughput of a single channel mesh network decreases as Big O(1/n), where n is the number of nodes or stations. In section 3.1.3 it is also explored how the TCP performance can degrade for this kind of problem. The main reason of degradation is due to the interference and MAC contention comes from each node. Therefore, if the co-located nodes are assigned different channel the performance can improve significantly. Hopefully 802.11b/g and 802.11a provided 3 and 12 non-overlapping channels respectively. Any way, as the number of available non-overlapping channel in IEEE 802.11 is limited; it is not possible to get rid from the interfering node completely. But the efficient allocation of channel can reduce the problem noticeably. Hence a lot of research activities are going on to assign the available orthogonal channel in such a way so that a node will not interfere to its nearby node during transmission and reception. It has been shown that efficient allocation of channel may boost the network performance up to 2 to 8 times the performance of conventional single channel mesh network (Raniwala 2004:50-65).

4.3. Previous work

Many commercial and research projects have been trying to make the best use of the wireless mesh network technology. Although there have been several research efforts that aim to exploit multiple radio channels in an adhoc network, most of them were made of proprietary MAC protocol (Garces 2000; Muir 1998; Nasipuri 1999; So 2003; So 2004) and therefore cannot be applied to directly wireless networks using commodity 802.11 interfaces (Raniwala 2004:50-65). Radiant Network (Radiant) and Mesh Network Inc. (Mesh Networks) are running two commercial Mesh network. Both architecture use proprietary hardware that is not compliant with 802.11 standards. Nokia introduced another commercial Mesh Network known as Rooftop Network (Nokia) that uses a dedicated channel for control signal and other channels for data in order to reduce the contention. An operating system called Nokia AIR OS is used in each router. Beam forming Antenna for each node is proposed in Transit Access point network (Karrer 2004).

Basically, the problem of channel allocation is alike the well known problem of graph colouring in computer science. It can also be treated as an optimization problem. The common approach to look for the allocation of channel is to first convert the wireless network into a simple graph where each station represents a node and each link represents a connecting edge. However, though the goal of the solution is same, the approach of the solution can varies from one method to another. Some algorithm solves it in a distributed fashion; some solves it in a centralized way. The required performance metric to allocate the channel also varies from one algorithm to another. Most of the recent works on multichannel 802.11 have looked for the solution of channel assignment as well as routing problem jointly.

Raniwala et al. (2005:2223-2234) proposed a distributed channel assignment algorithm for a multihop wireless network. The central issues of this algorithm are the efficient channel assignment and routing. The prototype network consists of 9 nodes. Each node is equipped with multiple 802.11 standards network interface card or NIC. The algorithm utilizes local traffic load information to dynamically assign channel and route packet. It is mentioned that the proposed solution can offer throughput 6 times the single channel backbone. The main drawback of the solution is, it only concentrates on the aggregate throughput.

Ramachandran et al. (2004) proposed an interference-aware channel allocation algorithm and corresponding channel assignment protocol. The proposed solution assigns channels to radios to minimize the interference with in the mesh network and between the mesh network and co-located wireless network. It utilizes an efficient interference evaluation technique in each mesh router. During channel setting the current flow is assigned to a default channel temporarily to avoid disruption of current flow. The OLSR routing protocol together with Weighted Expected Transmission Time (WETT) metric is used for route selection. They claimed that the solution can achieve 40% more performance when compared to static channel allocation technique.

Mishra et al. (2005) explored the possibility of using partially overlapping channel in wireless network. In his paper he proposed a specific mechanism that can transform partially overlapped channel into an advantage, instead of a hazard. The nodes where the number of interfaces is less than the number of non-overlapping channels provided by the physical layer can utilize this technique to communicate with other nodes in multiple channels.

Bong-jun et al. (2007:3978-3983) proposed a distributed channel allocation algorithm based on static data such as physical topology. A 14 node test bed was used to show the efficacy of the algorithm, each node was equipped with an 802.11a and an 802.11g card. It is shown that the algorithm improves the network capacity by 50 percent in comparison to homogeneous channel assignment and 20 percent in comparison to random channel assignment.

Shaan et al. (2005) devised a new way of keeping some monitoring node distributed in the wireless network. These monitoring node observe and store data about the traffic in the vicinity. These data are used by the proposed algorithm to determine the optimum channel to use in this place/time. It is observed that some cases the method can increase the performance up to 2 to 3 times the throughput of a statically allocated network.

Another kind of spatial partitioning is discussed by Hasio et al. (2004:3085-3089). It is shown that by introducing directional antennas, multiple simultaneously operable mesh network co-located in the same region can work together without introducing any interference.

Alicherry et al. (2005) proposed an algorithmic approach that optimizes the throughput. A method that maintains the network connectivity for QoS is proposed by Jiang Tang et al. (2005:68-77).

Many works previously done on channel allocation dealt with channel assignment algorithm with modified routing strategy. Some are application specific. Some introduced channel switching on packet by packet basis. However, the basic objective of channel allocation is to subdivide the network into several non-overlapping sub-networks in order to reduce the interference and MAC contention.

In our thesis work we divided the covered area between two non-overlapping channels and measured the performance metric by varying the covered area between two channels. The experiment shows that at a particular point of allocation the mesh network offers the optimum response and the throughput becomes 2 times the throughput of a single channel mesh backbone.

5. PROBLEM STATEMENT

5.1 Introduction

In this research, the prospect of dividing the total network area between two non-overlapping channels of a given Mesh Network, shown in Figure 5.1, is investigated and analyzed numerically. An extensive simulation studies have been carried out to find the optimum coverage area between two channels if any. In the following subsections the basic architecture of the proposed mesh network as well as the basic channel allocation strategy has been explored.

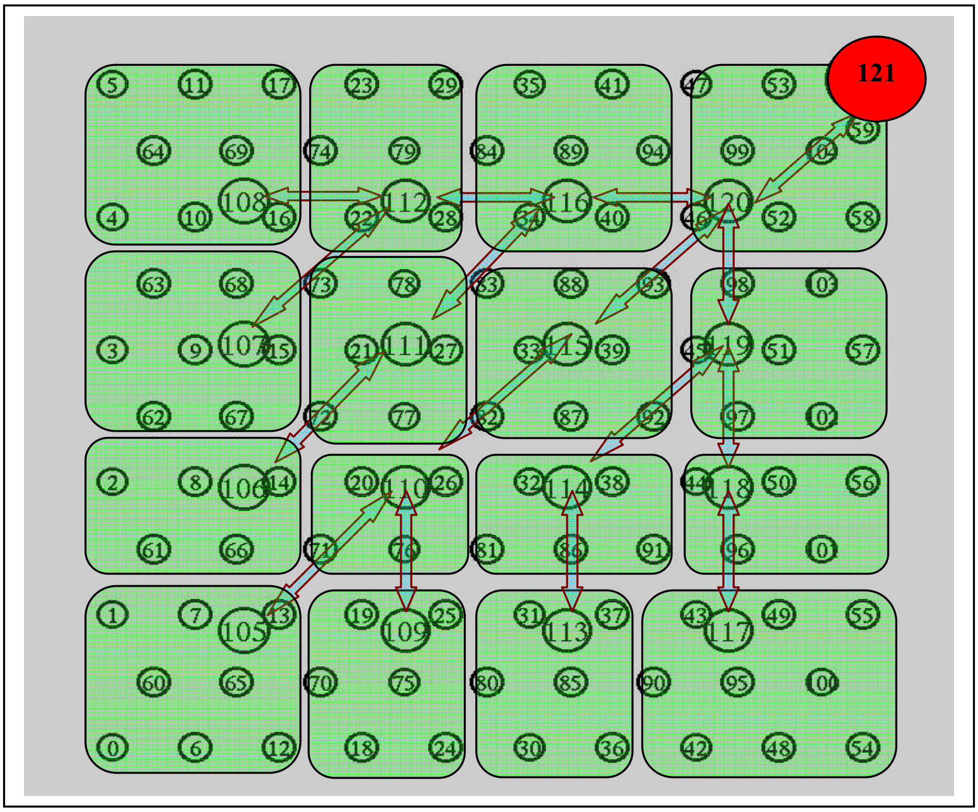

Figure 5.1. The basic structure of the proposed Mesh network.

As a whole, the aim of the channel allocation scheme is to maximize the throughput, minimize the delay and to improve the fairness among all nodes irrespective of their distance from the controller node.

5.2. System Architecture

The proposed wireless mesh network, shown in Figure 5.1 consists of 105 STAs, 16 Mesh points and a controller node. All nodes are static in nature. Small circles numbered from 0 to 104 are STAs and the medium size circles numbered from 105 to 120 are Mesh access points. The big red circle placed in the upper right corner, indicated by 121 is the controller node. All nodes are uniformly placed in a 400×400 meter square area. The Big arrow shows the routing path, optimized by ETT metric. The Mesh points are placed in a grid 85 meter apart from each other and form the backbone of the network. The backbone carries traffic to the controller node situated in the upper right corner of the network. The route between the STAs and controller node are fixed and optimized by ETT performance metric calculated by Floyd-Warshall algorithm. Each Mesh points act as a router as well as access point to the Stations and provide network connectivity to all STAs with in its coverage area. The Mesh points are equipped with two radios two channels and the STAs are equipped with single radio multi-channel NIC.

5.3. Channel Assignment Problem

The primary goal of this experiment is to investigate how the WMN responds if we divide the coverage area between two non-overlapping channels and secondly to examine if there is any optimum point of partitioning the area. The allocation strategy should be feasible and cost-effective. In order to do that the STAs are divided into two groups based on the coverage area as shown in Figure 5.2. The green coloured outer area belongs to one channel suppose channel 1 and the rest dark red inner area is covered by another channel suppose channel 2. Gradually the coverage area of the first channel is expanded towards the upper right corner and the corresponding performance for each case is examined. It is illustrated in Figure 5.2a and 5.2b how the area of both channel are varied. It is expected that at certain point of allocation the mesh network

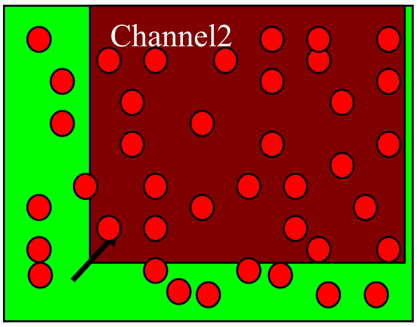

Figure 5.2a. The green area belongs to channel 1 and the rest inner area belongs to channel 2.

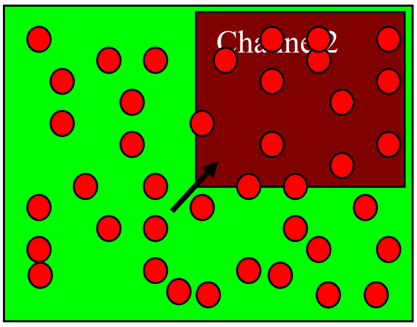

Figure 5.2b. The green zone is expanding gradually. The green area belongs to channel 1 and the rest inner area belongs to channel 2.

will give the best performance. Our aim is to investigate whether any optimum point of allocation exists and to examine how the proposed mesh responds at this optimum point of operation.

6. CHANNEL ALLOCATION STRATEGY

It was stated before that; the two channels are allocated based on the coverage area. In the following subsections the method of assigning area between two channels will be examined elaborately. It can be mentioned that the allocation procedure between two channels must be feasible and practicable.

6.1 Principle of allocation

Firstly our objective is to examine whether the performance of the mesh improves if we switch from single channel to multi-channel allocation. And secondly, the most important thing is to find out whether there is an optimum boundary for which the allocation provides the optimum result. In order to do that the area covered by two channels are varied step by step and in each step the performance of the mesh are examined numerically.

6.2. Assumptions

It is assumed that all nodes are static in nature and the MAPs and STAs are equipped with two radios two channels and single radio multi channel NICs respectively. The STAs are attached to its nearest mesh access point. The routing path is fixed and it was pre selected by the Site Designer (DACI 1990) result based on the ETT metric. During the performance evaluation phase the channels are assigned to the nodes manually.

6.3. Experimented Scenarios

In order to search for the efficient allocation of area between two channels we made 5 set-up or 5 scenarios as shown in Figure 6.1. The performance of each of this setting is evaluated separately. In Scenario1 to 4 the STAs are divided by two non-overlapping channels, channel 1 and channel 2. The coverage area of channel 1 is gradually expanding to the upper right corner as shown in Figure 6.1a to 6.1e.

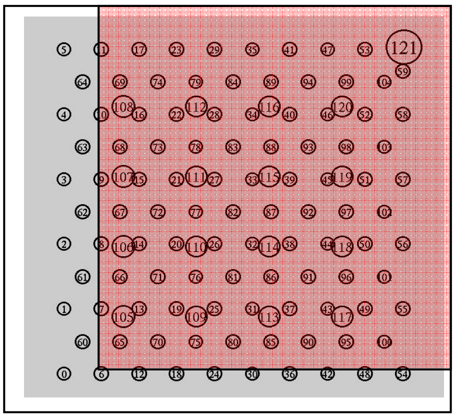

Figure 6.1a. Scenario 1, the blue coloured peripheral area are in channel 1 and the red coloured area are covered by channel 2.

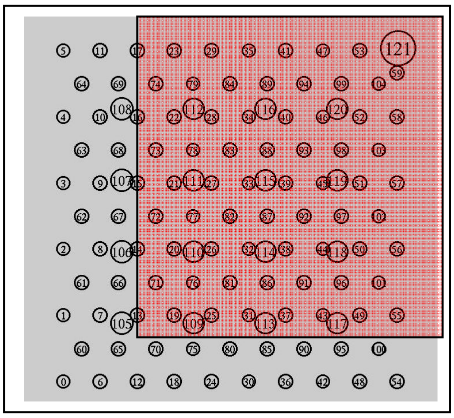

Figure 6.1b. Scenario 2, the blue coloured outer area are in channel 1 and the red coloured area are covered by channel 2.

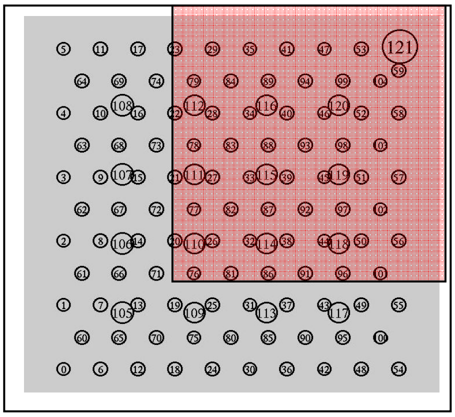

Figure 6.1c. Scenario 3, the blue coloured outside area are in channel 1 and the red coloured area are covered by channel 2.

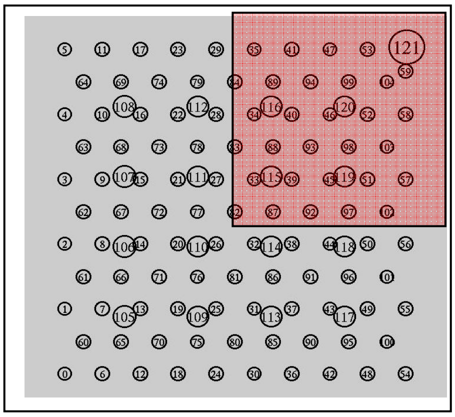

Figure 6.1d. Scenario 4, the blue coloured outside area are in channel 1 and red coloured area are covered by channel 2.

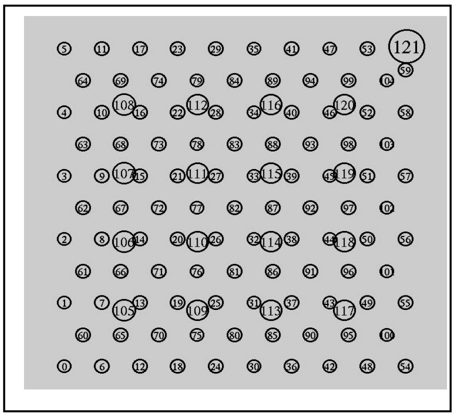

Figure 6.1e. Scenario 5, the red area is shrinked to zero. All STAs are covered by channel 1.

Figure 6.1. The coverage area of channel 1 are expanded manually towards the upper right corner as shown in Fig.6.1a to Fig.6.1e. In each step the area covered by channel 2 is shrinking gradually and in Scenario5 it is reduced to zero. The performance of each step is evaluated separately in subsequent chapter 7.

In Scenario 5 all STAs go under channel 1. However, in all cases STAs are associated with its nearest MAP.

6.3.1. Scenario 1

As shown in Figure 6.1a the STAs situated in the light blue coloured area are assigned channel 1 and the rest STAs in the red coloured area are assigned channel 2. The ratio of STAs between channel 1 and channel 2 is 20:85.

6.3.2. Scenario 2

The coverage area of channel 1 is expanded further towards the controller node shown in Figure 6.1b. As before the light blue coloured area is covered by channel 1 and the rest areas are covered by channel 2. Now the STA's ratio between two channels is 37:68.

6.3.3. Scenario 3

Here the area of the channel 1 is again stretched towards the controller node as displayed in Figure 6.1c. The STA's ratio between two channels is now 53:52.

6.3.4. Scenario 4

In this case a significant percentage of total area is covered by channel 1 as shown in Figure 6.1d. The ratio of STA between channel 1 and channel 2 has become 75:30.

6.3.5. Scenario 5

In this case, shown in Figure 6.1e, the area covered by channel 2 is shrinked to zero and all 105 STA s are working under channel 1, i.e.; the whole WMN is working in a single radio single channel.

7. PERFORMANCE EVALUATION

In order to study the complete performance of the mesh network we carried out extensive simulation study by NS2 (Information Sciences Institute) version 2.30. It is an open source discrete event simulator and gained a lot of popularity among the researchers all over the world. Ns2 is a popular academia mainly because of its extensibility.

7.1. Limitation of NS2

Although NS2 support wide-ranging unicast and multicast routing protocol as well as simulation environment for both wired and mobile wireless networks, still its support for the IEEE 802.11 standards needs to be enhanced a lot. The MAC layer does not support 802.11e EDCA standards and multiple interfaces for the nodes to transmit in multi-channel. The PHY layer is not efficient to offer various modulation techniques proposed in 802.11a/b/g. Up to version 2.30, NS2 has no provision for dynamic link adaptation based on signal to noise ratio. The newly proposed 802.11s for the mesh network is totally absent in existing NS2. In fact there are lots of things to do to get the actual flavor of the IEEE 802.11a/b/g/s standard from NS2.

7.2. Performance Metric

The ultimate goal of allocating channel is to get the maximum throughput, less delay and more fairness among the nodes. Besides throughput and delay, fairness is also a considerable factor for a multi-hop wireless network, as there are lot of chances for the far nodes to starve. However, to evaluate the performance of the proposed network we concentrate on three basic metric a) the aggregate throughput from mesh to controller node in transport layer b) the delay experienced by each node's TCP to send their packet to controller node's TCP and c) the fairness that is measured numerically by the standard deviation of throughput and delay.

7.3. Modeling and Configuration

Keeping in mind the shortcomings of NS2 for 802.11 standards, some extended codes are incorporated with the existing NS2 2.30 version to enhance its functionality. In the following subsection the modeling of different layers used in our simulation are described briefly.

7.3.1. Application or Traffic

Each STA has two constant bit rate (CBR) traffic sources, generating traffic at a rate of 5 packets per second, i.e.; the inter arrival rate of packets is 0.2 seconds. One source has packet size 220 byte and other has 2500 byte. All 105 STAs connected with mesh access points are sending packet through backbone to the controller node situated in the upper right corner of the network. The controller node has also CBR traffic sources connected to every station. The packet size is 2500 byte and generation rate is same as the STAs.

7.3.2. Transport Layer

In order to provide reliable transmission of packet, the primary requirement of the proposed traffic, the Transmission Control Protocol (TCP) is used.

7.3.3. Network Layer

Basically there is no provision in NS2 to provide ETT based route selection. Hence we used an extension called NOAH (No Ad-hoc 2007) to support fixed routing. The routes are selected in such a way that the packets experience minimum delay in their way to controller node and vice versa. These routes are taken from a previous experiment done by the Site Designer (DACI 1990), a popular network designing software tool.

7.3.4. MAC Layer

To access the medium, the CSMA/CA with RTS and CTS are used. An extension (Mhatre 2007) for Link adaptation is used to provide Auto Rate Fallback (ARF) algorithm based on the signal to noise ratio. A queue size of 2500 packet is used between the MAC and LL layer to get good performance. The impact of queue size in our experiment is also discussed in section 7.7.

7.3.5. PHY Layer

The shadowing is used as a propagation model. The various parameters of the model and the necessary threshold values of PHY layer are taken from the Site Designer (DACI 1990) Experimental result to optimize the system performance. The Antenna is Omni-directional. Antenna height, its gain, STA's and MP's transmitted power are also taken from the experiment done previously with the Site Designing software tool. The used values are given in the Appendix.

7.4. Results

The results for different scenarios are shown in the following subsections. The delay is measured by the time difference between a sender TCP first sends a packet and the packet is successfully received by the sink TCP. The throughput is measured in the transport layer, no ACK packets are considered while measuring the throughput.

7.4.1. Scenario 1

The figure 7.1a and 7.2a illustrate the cumulative distribution function (CDF) of delay of STAs and throughput for both channels respectively. The standard deviation of delay for channel 1 and channel 2 are 0.068s and 0.48s respectively. The aggregate throughput from mesh to controller node is around 2.58 Mb/s, where channel 1 offers around 1.14 Mbps and the channel 2 offers 1.437 Mbps separately.

7.4.2. Scenario 2

Figures 7.1b, 7.2b demonstrate the cumulative distributing function (CDF) of the delays of the STAs and throughput for both channels respectively. The standard deviation of delay for both channels is 0.345 s. The throughput of channel 1 and channel 2 to the controller node is around 2.548 Mbps. It seems that the Standard deviations of the delays for both channels are equal in this case.

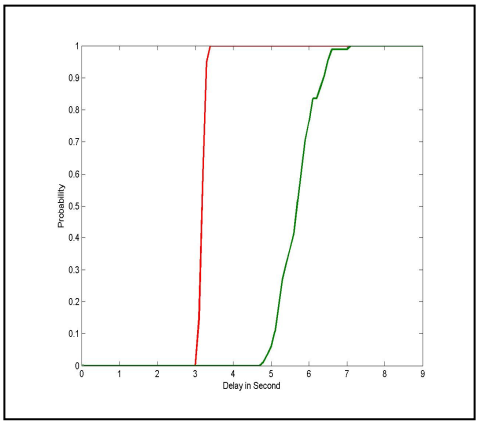

Figure 7.1a. The CDF of the delays of the STAs for CH1 (red) and CH2 (green) in Scenario 1. The Std. Dev. For CH1 and CH2 is 0.068s and 0.48 respectively.

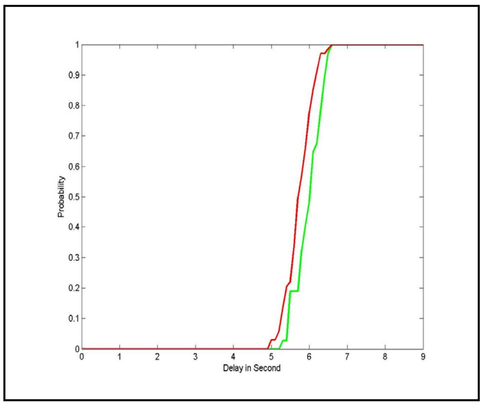

Figure 7.1b. The CDF of the delays of the STAs for CH1 (red) and CH2 (green) in Scenario 2. The Std. Dev. For both channel is 0.345s .

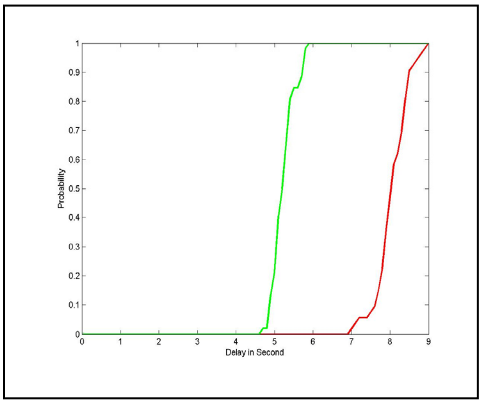

Figure 7.1c. The CDF of the delays of the STAs for CH1 (red) and CH2 (green) in Scenario 3. The Std. Dev. For CH1 and CH2 is 0.4114 and 0.290 respectively.

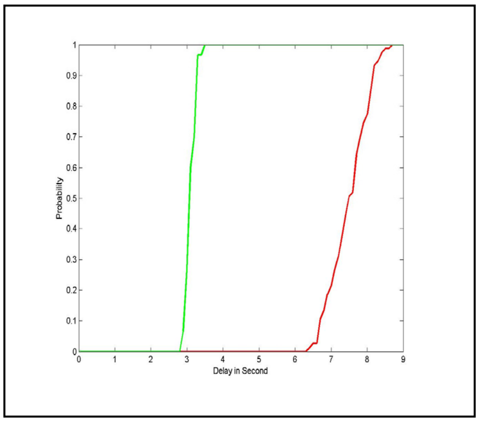

Figure 7.1d. The CDF of the delays of the STAs for CH1 (red) and CH2 (green) in Scenario 4. The Std. Dev. For CH1 and CH2 is 0.538s and 0.138 respectively.

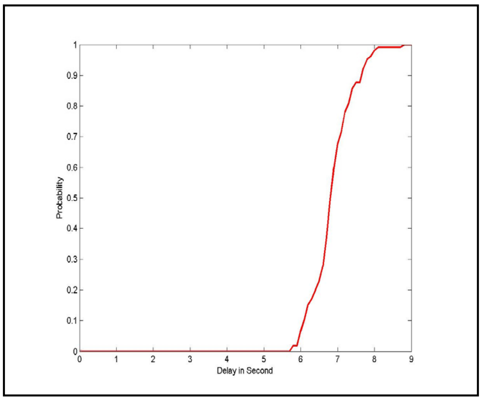

Figure 7.1e. The CDF of the delays of the STAs in a single channel in Scenario 5. The Std. Dev. Is 0.5539s.

Figure 7.1. The Standard Deviation of delay between two channels for Scenario 1 to Scenario 5 is illustrated in Figure 7.1a to 7.1e respectively. The red curve and blue curve represent CDF for channel 1 and channel 2 respectively.

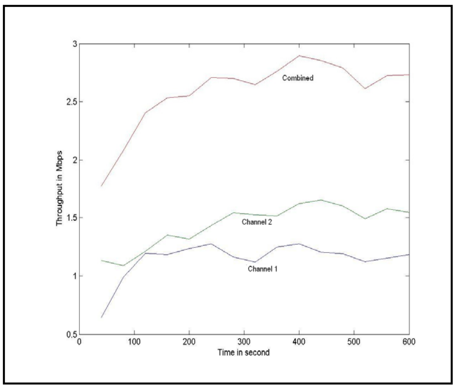

Figure 7.2a. The aggregate throughput from mesh to controller node for Scenario 1 in a 600 second simulation. The average is taken over 40 second intervals.

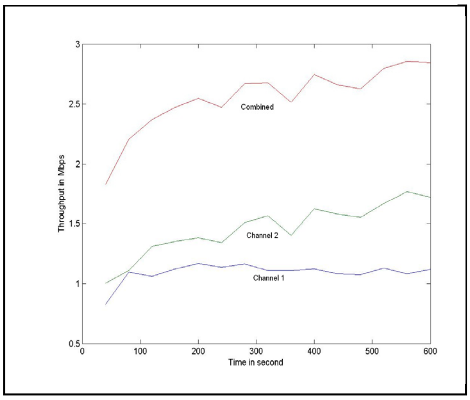

Figure 7.2b. The aggregate throughput from mesh to controller node for Scenario 2 in a 600 second simulation. The average is taken over 40 second intervals.

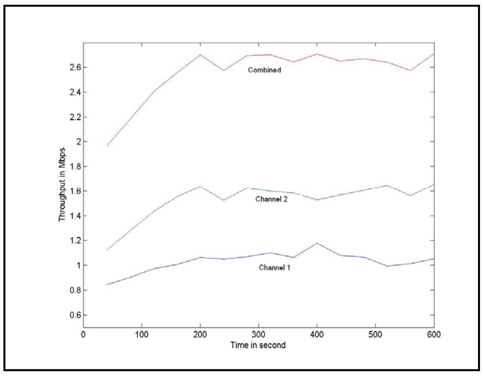

Figure 7.2c. The aggregate throughput from mesh to controller node for Scenario 3 in a 600 second simulation. The average is taken over 40 second intervals.

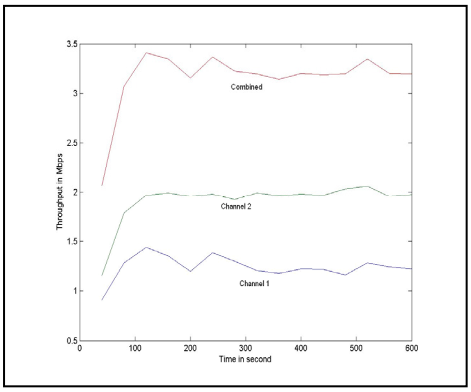

Figure 7.2d. The aggregate throughput from mesh to controller node for Scenario 4 in a 600 second simulation. The average is taken over 40 second intervals.

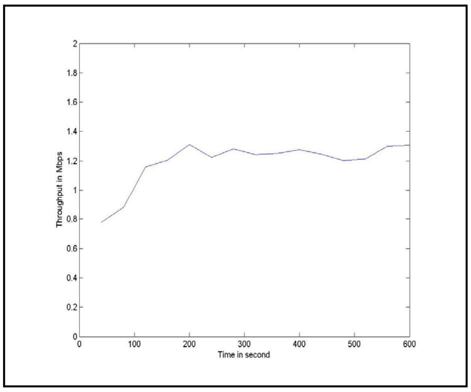

Figure 7.2e. The aggregate Throughput from mesh to controller node in a 600 second simulation for Scenario 5. The average is taken over 40 second intervals.

Figure 7.2. The aggregate throughput from mesh to controller node for Scenario 1 to Scenario 5 for CH 1 and CH 2 is illustrated in Figure 7.2a to 7.2e.

7.4.3. Scenario 3

Figures 7.1c, 7.2c display the Cumulative distribution function (CDF) of the delays of the STAs and throughput respectively. The standard deviation of the delays for channel 1 and channel 2 are 0.4114s and 0.290s respectively .The throughput of channel 1 and channel 2 are 1.0287 Mbps and 1.526 Mbps respectively. The total throughput from the Mesh to the Controller node is around 2.554 Mbps

7.4.4. Scenario 4

Figures 7.1d, 7.2d display the Cumulative distribution function (CDF) of the delays of the STAs and throughput respectively. The standard deviation of delay for the STAs is 0.538s and 0.138s for channel 1 and channel 2 correspondingly. The aggregate throughput from mesh to controller node is around 3.14 Mbps. The contribution from Channel 1 and channel 2 are 1.238 Mbps and 1.909 Mbps respectively.

7.4.5. Scenario 5

In this case all STAs belong to a single channel. The CDF of delay and throughput are shown in figure 7.1e and 7.2e respectively. The standard deviation of delay is 0.5539 s and the average throughput from mesh to controller node is 1.1895 Mbps. It is half of the throughput achieved before in scenario 1 to 4 where two channels were deployed.

7.5. Analysis of Network Fairness

In this section the performance of each scenario is reviewed spatially to have a closer look at the fairness offered to the STAs placed in different location. It was mentioned before that our goal is not only consider the throughput and delay but also make sure whether all STAs situated in different distances from the controller node are getting equal amount of service. In the following two subsections the spatial distribution of throughput and delay are studied numerically. The STAs are uniformly distributed over the 400×400 meter square area.

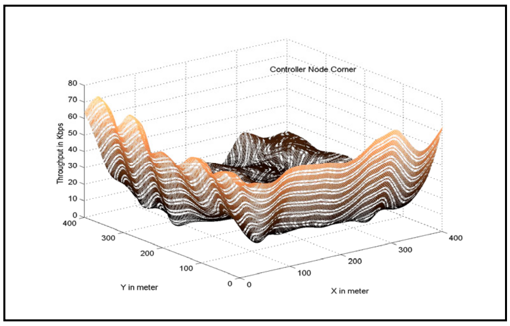

Figure 7.3a. Scenario 1, the individual throughput of the STA s in 400×400 meter square area. The STAs in the periphery are getting more privilege than the STAs in the upper right corner. The overall Std. deviation is 16.5 Kbps.

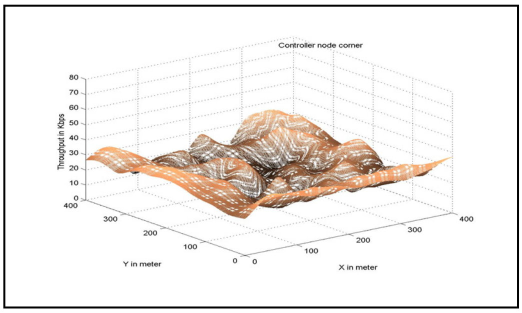

Figure 7.3b. Scenario 2, the individual throughput of the STAs in 400×400 meter square area. The diversity of throughput of the STAs near the controller node area and the STAs in the boundary area is less here. The over all Std. deviation is 6.5 Kbps.

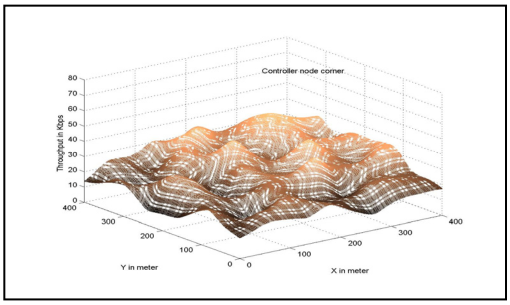

Figure 7.3c. The Throughput distribution of STA s over 400×400 meter square area in Scenario 3. The STAs near the boundary are getting less opportunity than that of the STAs situated near the controller node. The overall Std deviation is 6.81 Kbps.

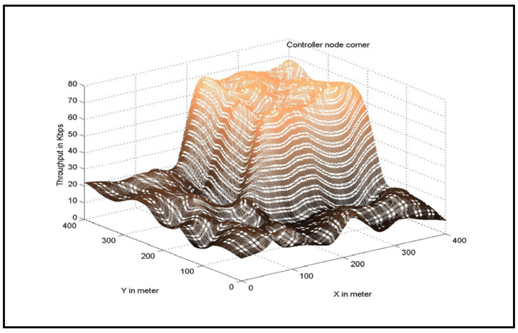

Figure 7.3d. For Scenario 4, the throughput distribution of STA s over 400×400 meter square area. The diversity of throughput between near and far STAs from the controller node is too high here. The over all Std. deviation is 21 Kbps.

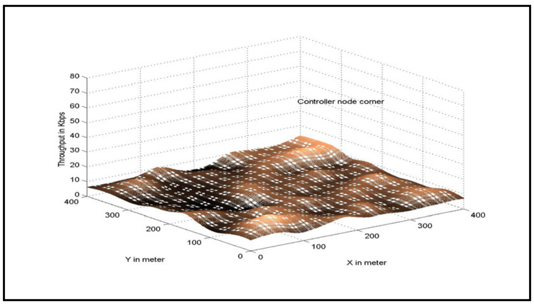

Figure 7.3e. Scenario 5, the throughput distribution of STA s over 400×400 meter square area. The surface seems very smooth, i.e.; the fairness is high here. The overall Std. deviation is 2.2 Kbps. However, the main drawback of this case is, the total throughput from mesh to Controller node is half of the throughput of other scenarios.

Figure 7.3. The spatial distribution of throughput of each individual stations for different scenarios are illustrated in figure 7.3a to 7.3e.

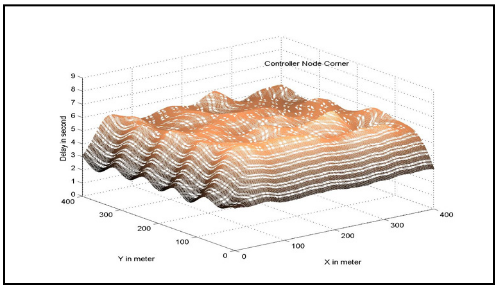

Figure 7.4a. The distribution of Delay of the STAs over 400×400 meter square area in Scenario 1.The STAs placed in the boundary are with less delays than those of the STAs in the upper right corner. The overall Std. deviation is 1.0766 s

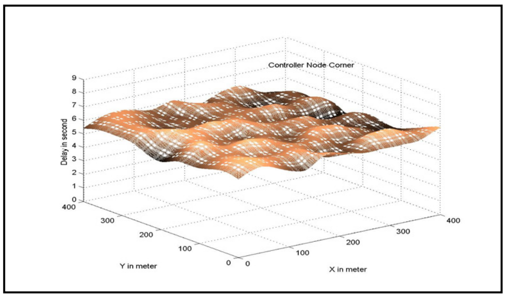

Figure 7.4b. The distribution of Delay of the STAs over 400×400 meter square area in Scenario 2. The STAs, all over the area are with more or less equal amount of delays. The Std. deviation of delay of STAs is 0.3645 s.

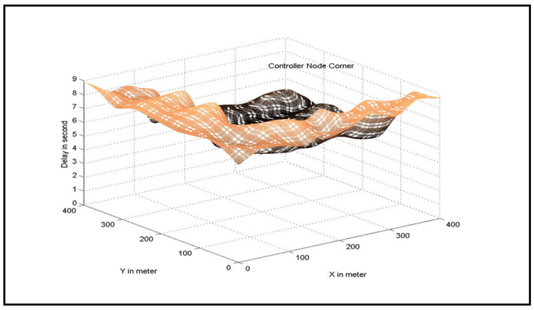

Figure 7.4d. The distribution of Delay of the STAs over 400×400 meter square area in Scenario 4. The STAs placed in the boundary are with more delay than that of the STAs in the upper right corner. The Std. deviation of delay of STAs is 2.035 s.

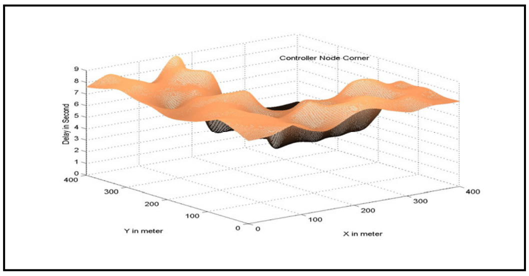

Figure 7.4d. The distribution of Delay of the STAs over 400×400 meter square area in Scenario 4. The STAs placed in the boundary are with more delay than that of the STAs in the upper right corner. The Std. deviation of delay of STAs is 2.035 s.

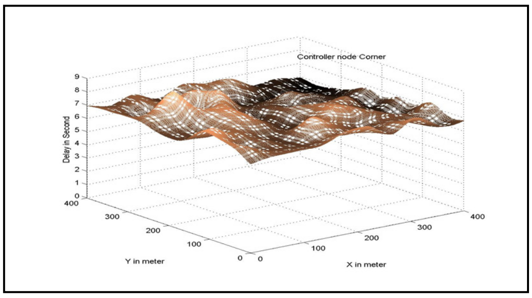

Figure 7.4e. The distribution of Delay of the STAs over 400×400 meter square area in Scenario 5. The STAs in the boundary are with more delay than that of the STAs in the upper right corner. The Std. deviation of delay of STAs is 1.895 s.

Figure 7.4. The spatial distribution of delay of each individual station for different scenarios are illustrated in figure 7.4a to 7.4e.

7.5.1. Distribution of Throughput

In Figure 7.3a, in scenario 1, it is seen that the STAs situated near the periphery and belong to channel 1 are getting more privilege than those of the STAs belong to channel 2. While the individual throughput of the STAs in channel 1 is around 70 Kbps, then the STAs belong to channel 2 are offering data at a rate of 30 Kbps. Any way, the situation improves a lot in Scenario 2 as shown in Figure 7.3b. The difference of throughput among the farthest and the nearest STAs reduces considerably in this set-up. All STAs irrespective of channel 1 and channel 2 are transmitting at a rate of 25Kbps to 30 Kbps. However, in case of Scenario 3, in Figure 7.3c, the fairness again starts to deteriorate. The far nodes here are putting data at rate 10 Kbps while the nearest nodes are putting at the rate of 35 Kbps. In Scenario 4, shown in Figure 7.3d, the deviation of throughput is very high. The throughput of the nearest node is as high as 70 Kbps while the far nodes have throughput of 10 to 20 Kbps only. The Scenario 5, in Figure 7.3e, where all STAs working in a single channel, exhibits very high fairness for all STAs. But any way, the major problem in this case is, the total throughput from the mesh to the Controller is about half of the throughput achieved in scenario 1 to 4.

7.5.2. Distribution of Delay

The spatial distribution of delay over the experimental area, for scenario 1 to 5 is shown in Figure 7.4a to 7.4e respectively. In Figure 7.4a it is shown that the delay of the peripheral STAs is much less than the delay of the inner STAs. In similar way, if we compare all the Figures from 7.4a to 7.4e, it is found that the scenario 2, shown in Figure 7.4b offers the smoothest surface over all scenarios. The overall Std. Deviation in this case is 0.3645 seconds. It is also observed that in this case the Std. deviation measured separately for each channel is also equal, 0.345 seconds each.

7.6. Analysis of Response

In this section the performance metric for different cases are analyzed numerically. On the basis of the previous results from section 7.4, a compiled data set for all Scenarios is given in table 7.1 below.

Table 7.1. Compiled data set for all Scenarios is illustrated here. In column 2 and 3 the Standard deviation of the STAs is calculated for each channel separately i.e.; during calculation the STAs those only belong to that specific channel are taken into account. On the other hand, for 'overall' cases, given in column 4, 5, and 9 all 105 STAs, irrespective of channel are considered.

Scenario	Std. Dev of delay in each channel separately (in second)		Overall Std. Dev. of delay (in second)	Avg delay/ node (in second)	Throughput Mbps			Overall STD Dev. of throughput among nodes in Kbps
	Ch1	Ch2	overall	overall	Ch1	Ch2	Sum	overall
Scene1	0.068	0.48	1.0766	5.208	1.14	1.1437	2.581	16.5
Scene2	0.345	0.345	0.3645	5.81	1.091	1.457	2.548	6.5
Scene3	0.4114	0.290	1.460	6.644	1.0287	1.526	2.554	6.81
Scene4	0.538	0.138	2.035	6.231	1.238	1.909	3.14	21
Scene5	Single channel		0.5539	6.8639	-	-	1.1895	2.25

Let first consider only the Scenarios 1 to 4 where two radios two channels are introduced. In case of average delay, Scenario 1 gives the minimum value, 5.208 s. The next higher value 5.81s is offered by Scenario 2. But if we compare the standard deviation of delay it seems that Scenario 2 is the fairest one above all Scenarios. It gives not only the least deviation when we consider 105 STAs altogether, but also gives the least deviation for channel 1 and channel 2 separately, and most interestingly both values are equal to 0.345 seconds as shown in table 1. Although in Scenario 2 the average delay increases from 5.208 to 5.81 seconds, but if both fairness and among the STAs as well as average delay are considered, definitely Scenario 2 is the optimum instance. It is also clear from Figure 7.4a to 7.4d that the Figure 7.4b gives the smoothest surface.

In case of throughput Scenario 4 gives the highest value of 3.14 Mbps among all multi channel Scenarios. Other Scenarios from 1 to 3 give more or less the same amount of around 2.55 Mbps. However, the problem in Scenario 4 is its large deviation of throughput among the STAs. The deviation is about 21 Kbps. It means that this instance does not provide equal amount of fairness to all its STAs. In Figure 7.3d, it shows that the STAs situated near the Controller node and belong to channel 2 are getting more privilege than that of the far STAs. It is also clear from Figure 7.3a to 7.3d and also from Table 7.1 that the Scenario 2 provides the fairest distribution of throughput to all STAs. If both throughput and fairness are taken into account, obviously the Scenario 2 is the best case.

Let compare Scenario 2 with Scenario 5, a single radio single channel instance. For delay and its Std. deviation, Scenario 2 shows better response than Scenario 5.

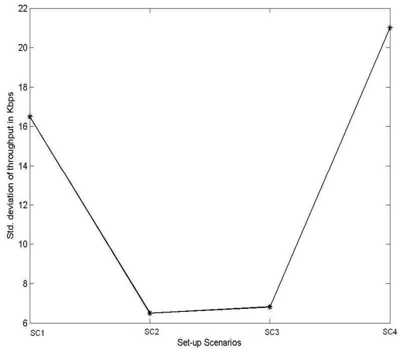

Figure 7.5a. Standard deviation of throughput among all STAs for different Scenarios. Scenario 2 gives the minimum value.

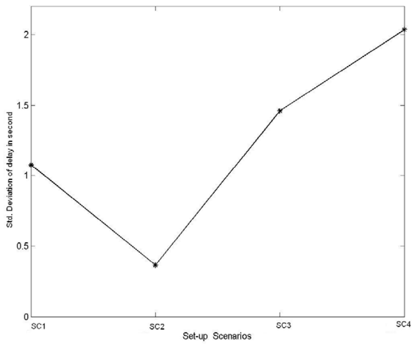

Figure 7.5b. Standard deviation of delay among all STAs for different Scenarios. Scenario 2 gives the minimum value.

Although the distribution of throughput over the network area is very smooth in case of Scenario 5 as shown in Figure 7.3e as well as in Table 7.1, the main drawback in this case is, the overall throughput from the mesh to the controller node is almost half of the offered throughput for other cases. Hence again it seems that Scenario 2 shows the optimum response over all Scenarios. Based on the data of the above results, the Standard deviation of throughput and delay for each Scenario are plotted in Figure 7.5a and 7.5b respectively. The Figures show that there is a minima and this minima is at scenario 2. Therefore, there is no doubt that an optimum point of allocation exists and scenario 2 in this case is that very optimum setting.

Any way, if we think about the performance metric, it seems that the aggregate throughput from mesh to the control node is not so high and the average delay for all cases needs to be improved further. The reason of this fact is mainly due to the interference created by all the nodes of this densely populated network. From the trace file it was seen that rarely two nodes of the whole network area transmit simultaneously. It means that the transmission of one node prohibit other nodes to transmit at the same moment, a common phenomenon of CSMA/CA protocol. For the same reason the wireless link between mesh and controller node acts as a bottleneck for the whole network, i.e.; the interference from the network enforces the gateway and controller node to stop transmission while other nodes are in transmission phase. This bottleneck builds a large queue in front of the gateway-controller link and increases the waiting time of the packets in the queue. Which in turn, add a large delay to the packet. The impact of queue on delay is further investigated in section 7.7.

However, from the above analysis it is obvious that introduction of two channels in the proposed Mesh enhances the network performance and this performance can be further improved by selecting suitable allocation of channel. The optimum point of allocation is that very point where the Standard deviation of the performance metric becomes minimum.

7.7. Impacts of Gateway Queue on Delay

Although each node has its own queue between LL and Mac Layer, we shall concentrate only on the impact of the queue size of the gateway node because of its considerable role on packet delay. It is found on the trace file that although the maximum queue size of the rest nodes are kept very small, packet rarely drops there. Actually the packet-drop happens at the Interface Queue (IFQ) of the Gateway node 120 shown in Figure 5.1. In reality, as the whole traffic of the network passes through the Gateway-queue it has a significant impact on the network performance. In the rest of the discussion the word queue will refer to only gateway queue.

The delay or time required for a packet to reach the Controller Node can be divided into two major parts, Delay = Time to get space in the head of the queue + Waiting time in the queue. For the sake of simplicity, let consider the queue size of the rest nodes of the network is constant as they have trivial role on packet drop. Under the above circumstance, we can simply represent our network as shown in Figure 7.6. Before discussing the impact of queue size on total delay (node->queue->sink) let have a look at the delay required for each node's packet to reach the Head of Queue (node->queue) of the Gateway. It can be mentioned that reaching the head of the queue and getting space in the head of the queue is totally different thing. A packet may undergo several retransmissions to get space in the head of queue for TCP.

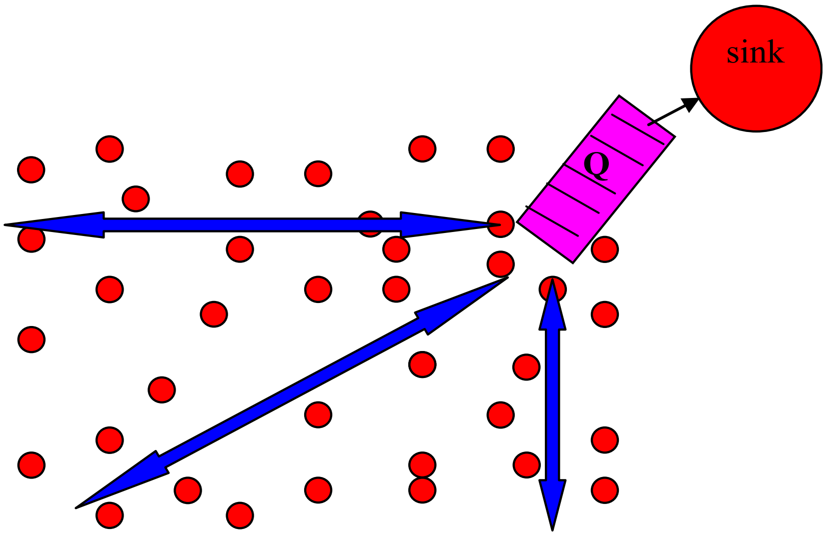

Figure 7.6. The simplified scenario at a glance. Red big circle is the sink node. The small red coloured node are sending packet to the sink by backbone through the common Queue shown in pink colour.

It is seen from Figure 7.8 that the nodes those are in the vicinity of the Sink are experiencing less amount of delay than that of far nodes to reach the queue. For the near nodes it is 10 to15 ms and for the periphery nodes it is around 100 to 150 ms, i.e.; 100 times greater than that of near nodes in this case. The two main things are clear from the Figure 7.8 , firstly, the time required to reach the head of the queue for the packet is in order of millisecond and secondly the packet from the near node are reaching the head of the queue quicker than the packet of the far nodes. Any way, if the packet irrespective from near or far nodes takes some millisecond to reach the head of queue then why the time to reach the controller node takes 5 to 7 seconds? The answer is, this extra large time is coming from the waiting time in the queue, or time requires for the packet to reach the tail of the queue from its head. If this is the fact, then will the delay improve if we set the maximum gateway queue size very small to reduce the waiting time?

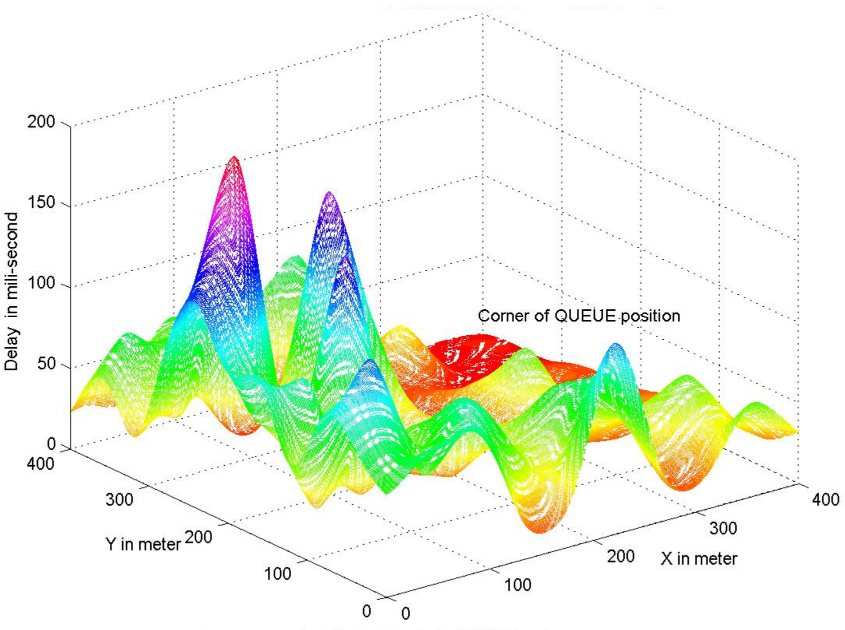

Figure 7.8 The distribution of individual delay of STAs in a 400×400 square meter area to reach the head of the gateway queue. For the near STAs it is 10 to 15 ms and for the far STAs it is 100 to 150 ms to reach. This means that the packet from the near STAs will fill the queue quickly if the queue size is very small.

In order to get the answer of this question let first consider two cases to find the impact of queue size on total delay (Node->queue->sink).

Case 1, Gateway Queue is very small: If the queue size is too small, the near nodes will fill the queue quickly. Most of the packets coming from the far nodes will be dropped. For this reason the far nodes will be deprived of the service as they are getting very less opportunity to put their packet in the queue; result, starving. But one thing, since the queue size is very small, the waiting time in the queue is also small, that’s why, the nodes those get the opportunity to put their packet in the queue will experience little amount of delay [O(ms)] . Results, small amount of total delay for those privileged nodes getting opportunity to place their packet in the queue.

Case 2 Gateway Queue is medium: Let increase the queue size. Now the probability of getting the space in the queue for far nodes will improve slightly and therefore after certain number of attempts (=packet drop) they will be able to get space in the queue. It is seen from Figure 7.10 that as the maximum queue size increases the amount of packet retransmission over the network decreases. As a consequence, the fairness also improves, as displayed in Figure 7.9. Since it takes several attempts for the far nodes to get room in the queue, the delay required for them to get space in the queue is higher naturally. The figure even might be 250 seconds to get space in the head of queue after five or six retransmission for some packet. As the queue size has increased, the waiting time in the queue has also increased. Hence successful near and far nodes those are getting the opportunity to place their packet in the queue will undergo more total delay [O(s)] than before.

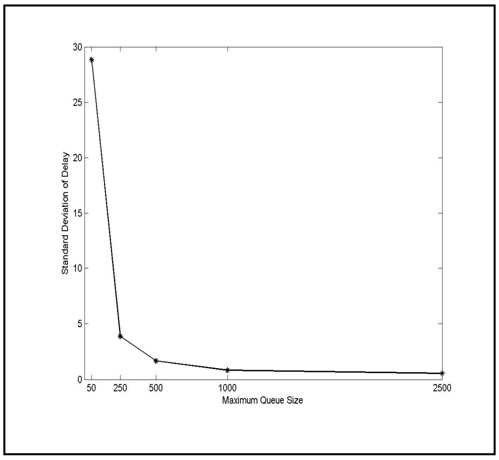

Figure 7.9. The Standard deviation of delay among all STAs for different maximum queue size is illustrated here.

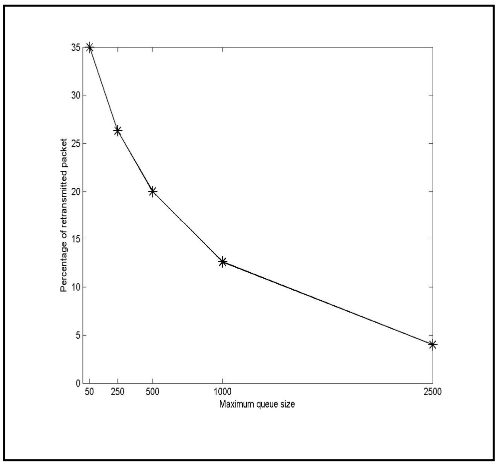

Figure 7.10. Percentage of retransmitted packet in a 600 s simulation for different maximum queue size is illustrated here.

In the similar fashion, the more we will expand the queue size the more fairness we will get up to a certain limit, because large queue enhances the probability for the far nodes to keep their packet in the head of the queue. As a result, at certain point, the standard deviation of delay among the nodes will improve significantly, as shown in Figure 7.9. It is noteworthy that as the queue size increases, the waiting time in the queue also rises for both near and far nodes.

It was found that for maximum 10000 size queue, the waiting time in the queue may be 7 to 10 seconds while the time to reach the queue is in the order of milliseconds. It clearly means that the large amount of delay is mainly coming from the waiting time in the queue. Basically queue size adjustment in this case, where the queue in front of the sink link acts as a bottleneck, is a trade-off between the fairness and delay. If fairness is not a primary factor then we can offer less delay to a certain percentage of nodes and if we want more fairness, nodes will encounter more delay.

However, it can be mentioned that delay will also adjust the window size of the node's TCP and slow down the packet transmission rate. It is one kind of closed loop control system, where ACK packets, as it were, acts as a feedback signal.

7.8. Impacts of Very High Capacity Gateway-Controller Link on Delay and Throughput; an Ideal Case Analysis.

As the link (120,121) acts as a bottleneck of the given mesh network, a dedicated channel or some other contrivance for that link could improve the mesh performance. In this section, we shall try to have a look how the mesh will act if this blockage is removed completely. Any way, this ideal case simulation will help us in future to inspect other major factors inside the backbone affecting the overall performance.

Let assume, this particular link has infinite capacity. Therefore the packet will take zero second to reach node 121 from node 120 or vice versa. For the sake of simplicity, if this instance is thought in electrical circuit domain, it appears that both nodes are in equal potential and act as a common ground for the whole network. The reverse condition is also true. Under the above condition, arriving at node 120 is the same as arriving at node 121 for the data packets. This simplified case can be easily implemented by existing NS2. What we have to do is to shift all traffic-sink and traffic-source to node 120 from node 121.

The simulation was run for single channel set-up where link (120,121) has infinite capacity. It is found that the transport layer throughput (excluding ACK packet) becomes 4Mbps. The average TCP delay for nodes is now 36.13 ms and the standard deviation of delay among the STAs is 36.38 ms. *If we compare it with previous result, it seems that the throughput rises from **1.18 Mbps to 4 Mbps** and the average delay experienced by STAs improves from **6.86 seconds to 36.13 milliseconds.***

7.9. Effect of STA's Distribution on Optimum Boundary Location

In this section an additional experiment has been carried out to find the effect of distribution of STAs on the location of the optimum boundary. The simulation is run for a non uniform distribution of STAs. The coverage area between two channels is varied as before. The setup for this experiment is shown in the Figure 7.11 above. The routing

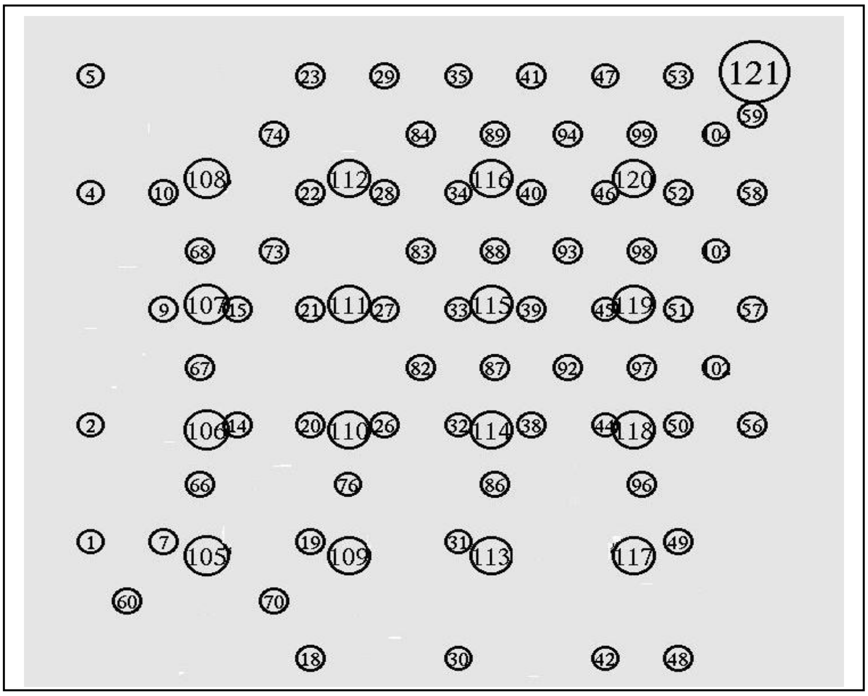

Figure 7.11. STAs are distributed non-uniformly over the 400×400 metre square area.

paths are kept unchanged. STAs will be attached to its nearest MPs to form clusters as before. The data for the different scenarios are given in table 7.2. It shows that the deviation of delay and throughput among STAs is minimum in Scenario 3. It means that there is an optimum point around scenario 3.

Table 7.2. The standard deviation of delay and throughput among the STAs for different scenarios are given here. It seems that the scenario 3 has the best value.

Scenario	Std. Deviation of delay in second	Std. Deviation of Throughput in Kbps
SC1	1.7783	28.871
SC2	1.1479	19.913
SC3	0.6344	7.286
SC4	1.4878	18.29

In the previous case where STAs were uniformly distributed we found the optimum point around Scenario 2. Any way, the study above proves that the location of optimum boundary is not fixed; it can shift under different situation or for different distribution of STAs. However, this shifting property confirms the necessity of looking for a suitable boundary dynamically.

8. CONCLUSION AND FUTURE WORKS

Mostly due to the MAC contention in a Multi-hop Wireless Mesh network it is difficult to extract its full potential in case of traditional single channel backbone. The facility of using multiple channels, available in 802.11a/b/g standard enhances the bandwidth available to the wireless nodes considerably. In this thesis, the potentiality of using two-channel backbone in a given multi-hop Mesh network has been analyzed numerically. The two channels are allocated on the basis of coverage area. The study shows that at a particular point of allocation the network gives the optimum response. It is found that by deploying two NIC to several MPs, the throughput improves two times when compared with single NIC per MP. The delay as well as the fairness also improves in case of efficient allocation of area between two channels. At optimum point, the stations irrespective of their location offer more or less same amount of output per unit time and experience almost equal amount of delay to reach the controller node, i.e.; a fair response can be achieved. It can be mentioned that this optimum point is not a fixed point; its location can depend on the spatial distribution of the STAs.

The study also shows that the link from the gateway to the controller node acts as a major bottleneck of the mesh backbone. This bottleneck builds a large queue in the gateway node that degrades the network performance significantly. Although it takes several millisecond for the packet to reach the head of the gateway queue, it takes extra 5 to 6 second to traverse the single-hop gateway-controller link, i.e.; the average queuing delay of a packet is more than 150 times the delay to reach the head of the queue. Hence a special mechanism must be deployed to increase the capacity of the gateway controller link to reduce this enormous amount of queuing delay. It is also shown that in case of a very high capacity gateway controller link the total delay can be improved from 6 seconds to 36 milliseconds. This is really a very promising result.

In future the above phenomena can be studied mathematically more accurately. We can model our system as a G/G/1 queuing system.

Where the delay bound $\leq \lambda \frac{(\sigma_x^2 + \sigma_y^2)}{2(1-\rho)}$

σ_x^2 =variance of service time (in our case the dispatch rate from the queue)
σ_y^2 =variance of inter arrival time of packet in the queue
ρ =utilization factor (arrival rate×expected service time)
λ = arrival rate of packet

We need to evaluate these above parameter from the trace file to give a mathematical model if possible. Up to now we can not tell what type of probability distribution the packets are experiencing.

However, the simulation result seems quite promising and demands more investigation in future. In order to further improve the response, we can concentrate on the following points.

- As the link from mesh to the controller node is the major bottleneck, what will be the performance if we allocate a dedicated channel for that link? It is expected that this may improve the performance considerably. Besides this, can we deploy the MIMO technology for that link?
- How much improvement can be achieved if we give overloaded links higher priority than low traffic links by 802.11e EDCA MAC? Again, what will be the priority factor?
- What will be the performance if we deploy three or more non overlapping channels?
- How does the optimum boundary shift in case of non uniform traffic or non uniform distribution of STAs? Do multiple optimum points exist?
- What measures should be taken in case of link failure?

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APPENDIX A. THE USED PHY PARAMETERS IN SIMULATION

Table A1. Parameters and their defined values for MAPs

Carrier Frequency	5GHz
Data rate (Maximum)	54Mbps
Data Rate (minimum)	6Mbps
Carrier Sense Sensitivity	-89 dBm
RX Sensitivity(for maximum data rate)	-88 dBm
RX Sensitivity(for minimum data rate)	-73 dBm
Tx Power	0.025 W
Antenna Gain	6 dB

Table A2. Parameters and their defined values for STAs

Carrier Frequency	5GHz
Data rate (Maximum)	54Mbps
Data Rate (minimum)	6Mbps
Carrier Sense Sensitivity	-87 dBm
RX Sensitivity(for maximum data rate)	-87 dBm
RX Sensitivity(for minimum data rate)	-72 dBm
Tx Power	0.1 W
Antenna Gain	6 dB