QoS Evaluation of the WLAN IEEE 802.11e

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ABSTRACT

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Wireless networks have a variety of advantages making them very popular in various applications. As the use of wireless networks increases, so does the demand for better service in terms of less delay for voice and video traffic. In 1990 the IEEE 802.11 was defined as a wireless network standard, yet this standard lacks traffic differentiation techniques to provide time-efficient service. The Work Group "e" has been working on enhancing the service since end of 2002; currently it defined a draft that will be the future standard to enhance the service. This new standard will enhance the use of wireless networks in time sensitive applications such as videoconferencing and voice over the internet protocol (VoIP).

This study evaluated and suggested enhancements for the service performance of the defined IEEE 802.11e draft. It is essential to assess the performance of the draft, as it will be the baseline standard for all the IEEE 802.11 wireless network vendors. The results of this work show that legacy networks (networks without the IEEE 802.11e implementation) perform better than the IEEE 802.11e networks under single kind of traffic (either data, voice or video traffic). Considering such conclusions is critical for businesses when making decisions to upgrade or forgo purchasing costly equipment. Improvement suggestions to the upcoming IEEE 802.11e were made based on simulation results to change the default value of some parameters to achieve better performance under mixed traffic. The simulation results also show that the IEEE 802.11e provides priority to voice and video over data traffic.

Words of Thanks

I would like to express many thanks to all my Electrical Engineering professors for their skilled and valuable instruction. Great appreciation and thanks are given to my thesis supervisor Professor A. Agarwal who planted in me the research spirit. The successful completion of this thesis is a testament of the professional education received at Concordia University and my practical application of the learned concepts.

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Dedication

To my wonderful and supportive parents

My Father *Mr. Farouk Youssef*

&

My Mother *Mrs. Nadia Youssef*

With all my love and appreciation

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List of Acronyms

AC	Access Category
AP	Access Point
BSS	Basic Service Set
CFP	Contention Free Period
CP	Contention Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordinating Function
DIFS	Distributed coordinating function InterFrame Space
DSSS	Direct Sequence Spread Spectrum
EDCF	Enhanced Distributed Coordination Function
EIFS	Extended InterFrame Space
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
HCF	Hybrid Coordination Function
HIPERLAN	High PERformance radio LAN
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	InterFrame Spaces
ISO	International Standards Organization
LAN	Local Area Network

LLC	Logical Link Control
MAC	Medium Access Control
Mbps	Mega bits per second
MPDU	MAC Protocol Data Unit
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
OPNET	Optimized Network Engineering Tools
OSI	Open System Interconnection
PC	point coordinator
PCF	Point Coordinating Function
PDA	Personal Digital Assistant
PIFS	Point coordinating function InterFrame Space
QAP	QoS Access Point
QoS	Quality of Service
QSTA	QoS Station
RF	Radio Frequency
RTS	Request to Send
SIFS	Short InterFrame Space
TBTT	Target Beacon Transition Time
TXOP	Transmission Opportunity
VoIP	Voice over Internet Protocol
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 What is QoS WLAN?

Communication networks have become a necessity in an increasingly modern and busy world. In the beginning of the computer network era, networks were used for applications that are not time critical (such as e-mail and data transfer), and computers were huge taking up tremendous space. Currently, the Internet is a major information infrastructure supporting numerous real-time applications (time critical applications, like video conferencing and Voice over Internet Protocol (VoIP)). The increase in the use of real-time applications has increased the demand for network Quality of Service (QoS). QoS is a measure of how a network provides consistent network data delivery [1]. It can be measured in terms of packet loss (dropped data packets that did not reach the destination), delay (how long it takes for a user's packet to get to the destination), jitter (variation in delay because packets are held in a buffer until the output link becomes available) and data-rate (how much data can continuously be delivered to a destination).

With the advancing of technology, computer size is decreasing dramatically so that they have now become lightweight hand held devices, allowing the mobility of the users. For the portable users to be connected to the network or the Internet, a Wireless Local Area Network (WLAN) is needed. WLAN is a network that uses the air as the medium of information transmission rather than copper or fiber optic cables used in wired networks.

Portable users require a WLAN with high QoS for them to be able to run real-time applications. Providing such networks has became the challenge of the communication industry today due to the air atmospheric interference and data packet collisions encountered by mobile terminals while contending for the medium. This thesis studies the QoS of the WLAN standard IEEE 802.11 and will evaluate QoS performance of the up and coming IEEE 802.11e extension of this standard.

The IEEE 802.11 is a WLAN standard lacking traffic differentiation mechanisms that would otherwise provide better service for voice and video traffic. The Work Group "e" (WGe) was formed to enhance the IEEE 802.11 standard by providing techniques for service differentiation. In the end of 2002, the WG defined a draft of the required enhancements that will later be standardized. In this research we attempt to evaluate and assess the performance of the upcoming IEEE 802.11e standard, and to provide suggestions based on simulation results to achieve optimal quality of service from the new standard.

1.2 Advantages and Applications of WLANs

The use of wireless networks has increased in the past years, and it is now not just a luxury, but rather crucial to the survival of many businesses. Thus WLANs are now being deployed in many places such as [2]:

- Hospitals: where WLANs are used to record and deliver patient information within the hospital.
- Universities: where WLANs provide network connections for students with laptops. Also, professors can access the network from the classrooms without wasting time locating ports.

- Restaurants: where the server will process the order via a handheld device at the table through a WLAN connected device. A screen in the kitchen connected to the network will display the order, hence speeding up preparation of the food for hungry customers.
- Inventory: control for wholesale and retail applications. In a warehouse, an employee walks through the aisles with a handheld device connected to the network and takes record of the inventory.
- Internet service in public area such as airports, hotels and train stations. This is useful for travelers or business people constantly on travel for checking e-mails and business messages.

Increasing popularity of WLANs is due to their many advantages for individual users and businesses over the wired networks, some of which are [3]:

- Mobility: Users connected through the WLAN can access real-time information on the go.
- Quick and easy installation: Installing a WLAN is fast and simple, not requiring the installation of many cables. This is useful in some manufacturing and warehousing buildings, where it is costly and time consuming to install wires to build the infrastructure of a Local Area Network (LAN). WLANs can easily and cheaply be installed in such environments.
- Transparent to the user: Application works the same way using WLANs as they do on wired LANs. Hence, minimal learning time is needed.
- Low power: Wireless networks use the highest technology to increase usage of battery life.

- WLAN network scalability: WLANs can be configured in different topologies (structure or layout). Configurations range from peer-to-peer networks suitable for small businesses to full infrastructure networks as in universities.
- Safety: WLAN systems have very low output power compared to the hand held cellular phone. Thus, those in the area of a WLAN receive little exposure to the Radio Frequency (RF) energy.
- Compatibility with wired networks: WLANs are compatible and can be interconnected with the wired networks. The network operating system treats the WLAN node in the same fashion as any other LAN node.

1.3 Objectives and Motivation

The objective of this work is to evaluate the performance of the IEEE 802.11e draft, and measure the achieved improvements compared to the IEEE 802.11. Also, this work will help fine-tune the draft that is expected to be the future standard for QoS in IEEE 802.11. Practical direction was undertaken in this work by using realistic traffic source models and network topologies to model real live scenarios. This work will contribute in finding the best configuration setting to obtain the optimal QoS from the upcoming IEEE 802.11e standard.

As pointed out in section 1.2, WLANs have a lot of advantages and are spread out in different applications. WLANs now provide network connection for hundred of thousands of users everyday. Section 1.1 showed that the WLAN multimedia and real-time applications traffic is increasing with the increase of the use of WLANs. The increase of the high priority traffic increased the demand for QoS WLAN. The IEEE 802.11e draft is defined to provide traffic differentiation for IEEE 802.11 network and hence improve the QoS. Currently there are about sixty WLAN equipment vendors with more than two hundred different WLAN products. Having many vendors with a wide range of WLAN products necessitates a standard method to efficiently provide WLANs with QoS for achieving interoperability among all products. The IEEE 802.11e draft will affect all the WLAN users requiring QoS network. The spread of the use of WLAN and the need to improve the QoS has provided the motivation to work in this area.

1.4 Thesis Organization

This thesis is organized into five chapters. Following the introduction of chapter 1, chapter 2 will explain the two main WLAN standards with an emphasis given to the IEEE 802.11 standard. Chapter 3 will point out some QoS limitations with the current IEEE 802.11 standard and will present the draft with other solutions in the literature to improve the QoS of this standard. Among the presented solutions is the upcoming extension of this same standard, namely the IEEE 802.11e. Chapter 4 will present an evaluation of this extension using simulation results and will provide suggestions for fine-tuning the "e" extension to obtain the optimal QoS results. Finally, in chapter 5 the thesis is concluded, with directions for future work.

Chapter 2

IEEE 802.11 WLAN Standard

In 1990, the Institute of Electrical and Electronics Engineers (IEEE) formed a committee to develop a standard for wireless LANs operating at 1 and 2 Mega bits per second (Mbps) [4]. In 1992, the European Telecommunications Standards Institute (ETSI) charted a committee to establish a standard for high performance radio LANs (HIPERLAN) operating in the 20 Mbps range [5]. This Chapter explains the IEEE 802.11 MAC sub-layer, while the physical layer is presented in Appendix A. Understanding the MAC sub-layer and its functionality is very important for this thesis in order to be able to find the QoS limitations with the IEEE 802.11 standard and understand the improvements presented in the IEEE 802.11e revision.

2.1 IEEE 802.11 Standard

The IEEE 802.11 is a standard for WLAN. It is based on the Open System Interconnection (OSI) model of the International Standards Organization (ISO). The OSI is a reference model for describing network protocols; it divides a data communication protocol into seven distinct layers to standardize and simplify definitions. The seven layers of the OSI reference model are: physical, data link, network, transport, session, presentation and application. The IEEE 802 group of standards divide the data link layer into two sub-layers namely the Logical Link Control (LLC) and the Medium Access Control (MAC). The scope of the 802.11 study group is to develop specifications for both the MAC sub-layer and the Physical (PHY) layer. The MAC sub-layer is the heart of this thesis.

2.1.1 IEEE 802.11 Network Architecture

IEEE 802.11 defines network topologies enabling WLAN equipment to be configured in a variety of ways. End-point stations which are composed of laptops, Personal Digital Assistant (PDA) and handheld devices, are connected to the WLAN through a wireless network interface card. Understanding the wireless network architecture will be helpful in the next section in order to understand how the MAC sub-layer controls accessing the wireless channel.

There are two types of architecture. The first is the Independent Basic Service Set (IBSS) - the formal name of an ad hoc network [7] – which is the simplest type of configuration for the IEEE 802.11 network. Stations within the IBSS architecture can establish direct communication with one another without the need of delivering data traffic through a centralized Access Point (AP). Three people with laptops sitting in a room and connected to each other is a typical employment of the IBSS architecture, as shown in Figure 2. 1 [6].

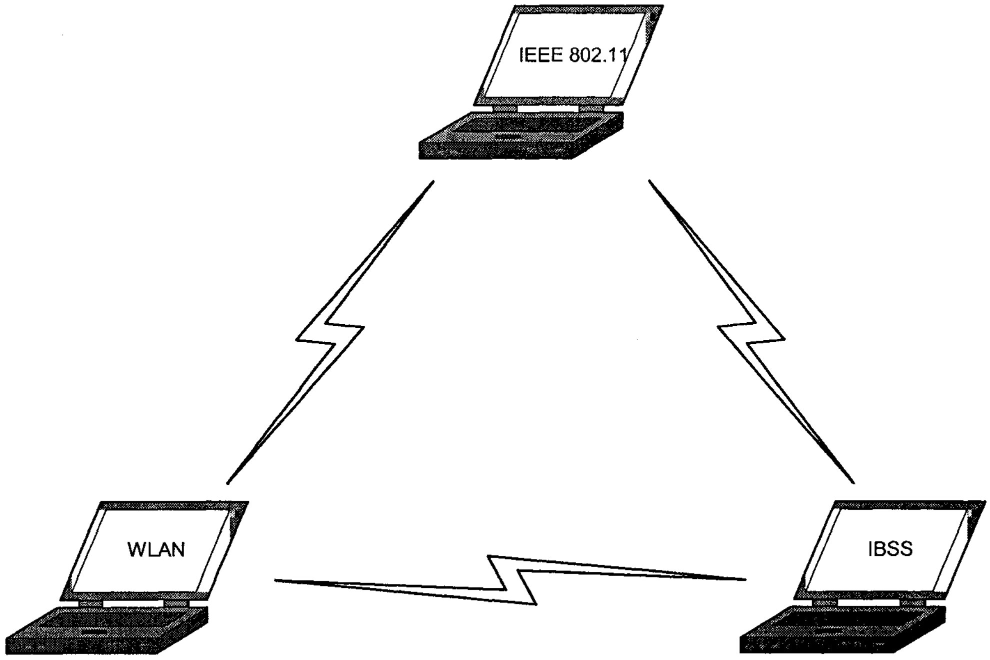


Figure 2. 1: IBSS Architecture

The second type of architecture is an infrastructure network called the Basic Service Set (BSS), shown in Figure 2. 2 [4]. The BSS is established using APs, which is analogous to the base station in a cellular communication network. The AP adds a gateway functionality enabling the BSS to be connected to a Distributed System (DS), a system used to connect BSSs together [2].

Each BSS functions as a single WLAN. Multiple BSSs can be integrated together using a DS to form an Extended Service Set (ESS) as illustrated in Figure 2. 3 [4]. The DS is solely used as a transport backbone network. It makes the decision whether to forward data traffic from one BSS to another or to a non-IEEE 802.11 network through a portal. Portals are logical entities specifying the integration point on the DS where the IEEE 802.11 network integrates with non-IEEE 802.11 networks.

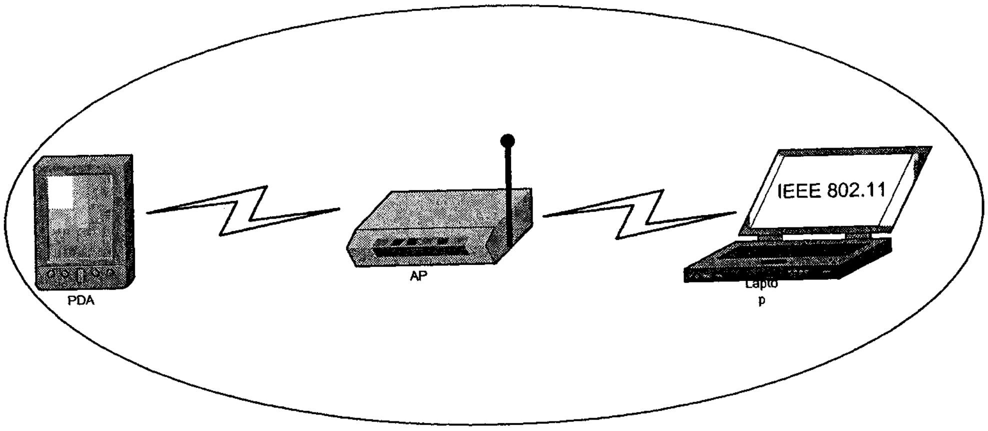


Figure 2. 2: BSS Architecture

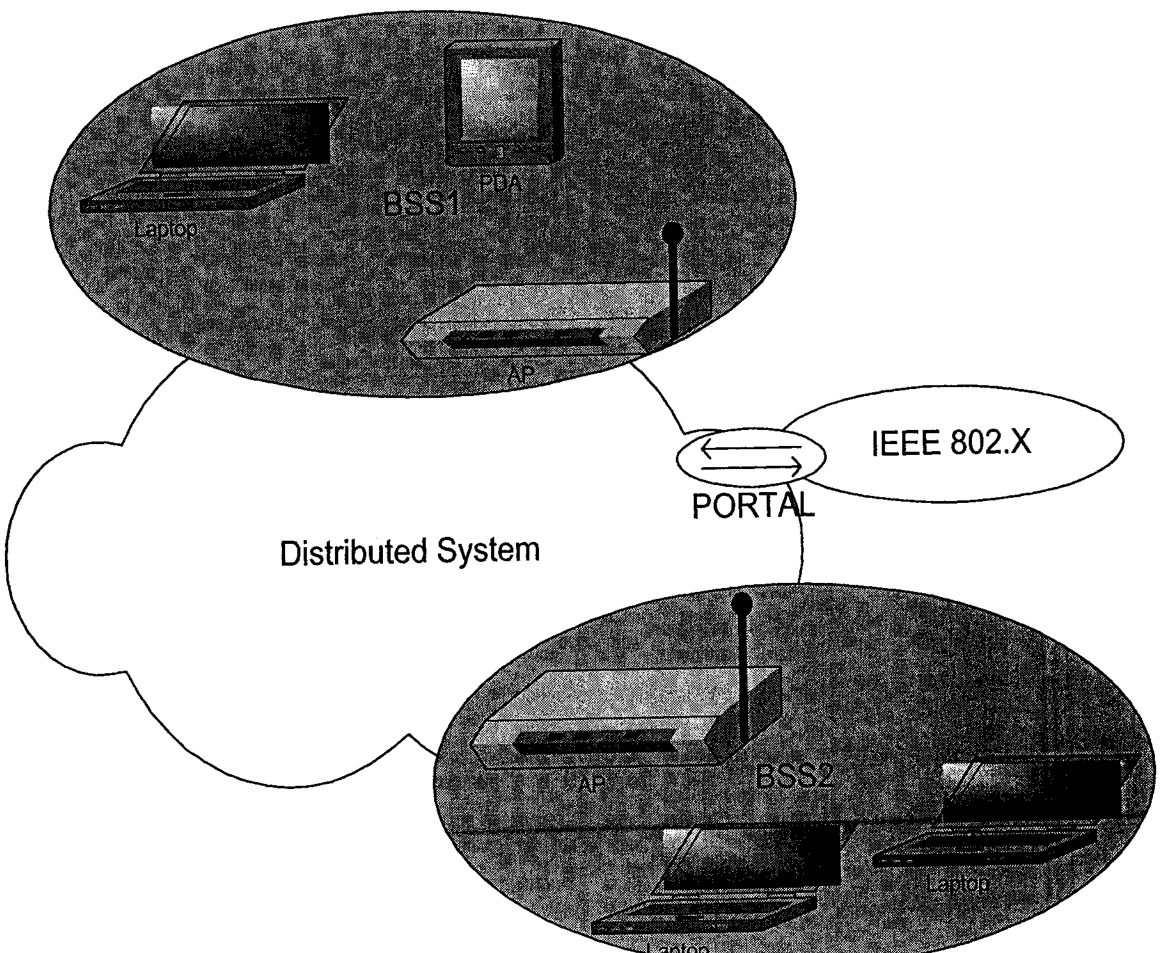


Figure 2. 3: ESS Architecture

2.1.2 Media Access Control

As mentioned before, the IEEE 802 protocols divide the OSI data link layer into two sub-layers, namely the LLC and the MAC sub-layer. This section presents the IEEE 802.11 MAC sub-layer. The LLC sub-layer is out of the scope of this work since the IEEE 802.11 standard specifies the MAC sub-layer only.

The functionality of the MAC sub-layer is: controlling channel access, frame formatting, error checking and fragmentation as well as reassembly of the data packets. The IEEE 802.11 MAC protocol provides two distinct coordination functions. Coordination function is a logical function that determines when a station in a BSS is permitted to transmit through the wireless medium [4].

The two distinct coordination functions are the mandatory Distributed Coordinating Function (DCF) and the optional Point Coordinating Function (PCF). The transmission medium can operate in the contention mode solely using the DCF, requiring all stations to contend for the wireless channel for each packet transmission. The period of time that the transmission medium operates in the contention mode is known as Contention Period (CP). The transmission medium can also alternate between the CP and Contention Free Period (CFP). During CFP, the PCF controls the medium; stations do not need to contend but rather get polled for transmission. Understanding the DCF and PCF is important in this thesis, as it will be the ground on which the IEEE 802.11e is build – the main focus of this thesis.

2.1.2.1 Distributed Coordination Function

The distributed coordination function is the fundamental access method of the IEEE 802.11 MAC sub-layer; all wireless network stations must support it. The DCF is based on best effort (with no QoS guarantees) and is used in transferring data that is not time sensitive. DCF gives equal probability for all stations to access the wireless medium. Hence there is no mechanism to guarantee minimizing the traffic delay to stations supporting real-time applications. In ad hoc networks, the DCF is solely used and could coexist with the PCF in an infrastructure network [8].

Collisions could occur when two or more stations transmit over the wireless channel simultaneously. Data corruption is the result necessitating retransmission. The DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol instead of CSMA/CD (Collision Detection). The collision detection method requires a full duplex radio frequency (combination of transmit and receive) or infrared pair of channels, making the station able to listen to the channel for collisions while it is transmitting. Deploying a full duplex radio frequency would increase the equipment price and size significantly. Since the collision detection method cannot be easily deployed, stations involved in a data collision will continue transmitting the complete data packet even though it had been corrupted. The continuation in the transmission results in wasting of the wireless medium bandwidth [4].

In order to minimize collisions (since it is impossible to completely eliminate them), the wireless stations can perform two levels of carrier sensing. The first one, physical carrier sensing, is performed by the physical layer at the air interface (wireless medium) by detecting activity in the channel via relative signal strength from other users. The second level is virtual carrier sensing performed by the MAC sub-layer. The channel is marked busy if either the physical or virtual carrier sensing indicates that the channel is busy. This sub-section focuses on the virtual carrier sensing and how it is used to reduce the wasted bandwidth and collisions. As will be presented in Chapter 3, virtual carrier sensing is used in IEEE 802.11e to improve the QoS of the WLAN around which this thesis is based.

Access priority to the wireless medium is controlled through the use of InterFrame Spaces (IFS). IFS is the time interval between frames. For IEEE 802.11, time is slotted in time periods corresponding to a Slot_Time used to define IFS. There are four types of inter-frame space [4]:

1. Short InterFrame Space (SIFS) is the shortest type of IFS and is used for all immediate response actions. For example, stations transmit an acknowledgment after SIFS interval of time from receiving an error free data frame. Also, stations respond with data SIFS interval of time after receiving the poll.
2. Point coordinating function InterFrame Space (PIFS) is longer than SIFS, and is used by the PC to gain priority access to the medium and start a CFP. This means that if the wireless medium is idle for PIFS interval of time then the PC will start the CFP by polling the stations.
3. Distributed coordinating function InterFrame Space (DIFS) is longer than PIFS and is used by DCF to enable the transmission of data and management of MAC Protocol Data Units (MPDUs). MPDU is the unit of data exchanged between two peer MAC entities. The use of DIFS will be clearer when explaining the backoff mechanism later in this sub-section.
4. Extended InterFrame Space (EIFS) is used to enable the process of frames reported to be erroneous by the PHY layer.

If a station with data to transmit detects that the medium is not idle (another transmission is in progress), the station refrains from transmitting. When the medium becomes idle for DIFS interval of time after a successful transmission or after each retransmission, the station refrains from transmitting for a backoff interval. This interval is determined according to the exponential backoff algorithm and referred to as backoff window. Each station decrements its backoff timer if the medium is idle during the backoff window and freezes the timer when the medium becomes busy. When the backoff counter becomes zero the station can start transmitting. The backoff interval grows exponentially as:

$$\lfloor 2^{2+i} * \text{Random}(0,CW) \rfloor * \text{Slot\_Time}$$

where i is the number of consecutive attempts to send an MPDU, $\lfloor y \rfloor$ is the rounding down nearest integer of y and Random(0,CW) is a random function between 0 and the Contention Window (CW) parameter. The CW is an integer within the range of values of the PHY characteristics $CW_{min} \leq CW \leq CW_{max}$. After each unsuccessful transmission attempt, the CW is doubled until it reaches a predefined maximum value CW_{max}. This will help in reducing the probability of collisions. After a successful transmission the contention window is reset to a predefined fixed value CW_{min} [4].

After the packet is transmitted, the receiving station checks if the packet is erroneous by using the Cyclic Redundancy Check (CRC) field. Error free packets are positively acknowledged by transmitting an acknowledgment frame (ACK). An unacknowledged packet will be retransmitted until it gets acknowledged or dropped after a given number of retransmissions.

A major reason for collision in WLAN networks is due to the hidden-node problem that occurs in an infrastructure BSS. In Figure 2. 4, Node A and B can hear each other as well as the AP. Likewise, Node B and C can hear each other as well as the AP since they are in the same BSS. However, Node A and Node C cannot hear each other because they are in different BSS, and because they have limited transmission range. A collision will occur if both Node A and C attempt to use the wireless medium simultaneously, resulting in corruption of the transmitted data from either Node A and C.

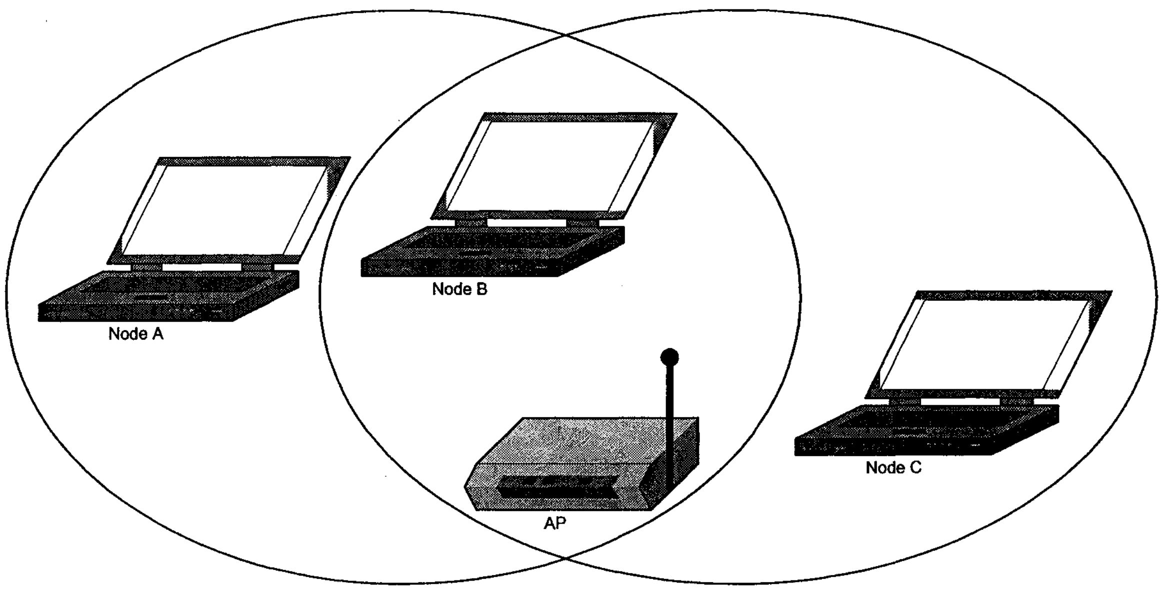


Figure 2. 4: Hidden Node problem. Node A and C cannot see each other

To overcome the hidden node problem, the RTS/CTS control frames can be used. Consider in Figure 2. 4, where Node C could be the source station having data packets to transmit to Node B. The source station (Node C) sends an RTS control frame containing source address, destination address, and the duration of the upcoming transaction (time to transmit data packet and the respective ACK). After SIFS idle interval is elapsed, the destination station (Node B) will respond with a CTS packet that includes the same duration information. If the source station did not receive the CTS frame, then it will retransmit the RTS packet following the backoff approach previously explained. Otherwise, if the source station receives the CTS frame, then it will transmit the data after the elapse of SIFS interval of time. The destination station receiving the data packet will positively acknowledge the data within SIFS interval using the ACK frames.

Stations other than the source and the destination which receive the RTS or CTS control frames, will store the duration field from the control frames as its Network Allocation Vector (NAV). NAV indicates the amount of time that must elapse until the current transmission session is complete and the channel can be sampled again for idle status. Stations other than the source and destination will refrain from transmission after receiving the RTS/CTS and updating their NAV's. The frame exchange, used in virtual carrier sensing, is illustrated in Figure 2. 5.

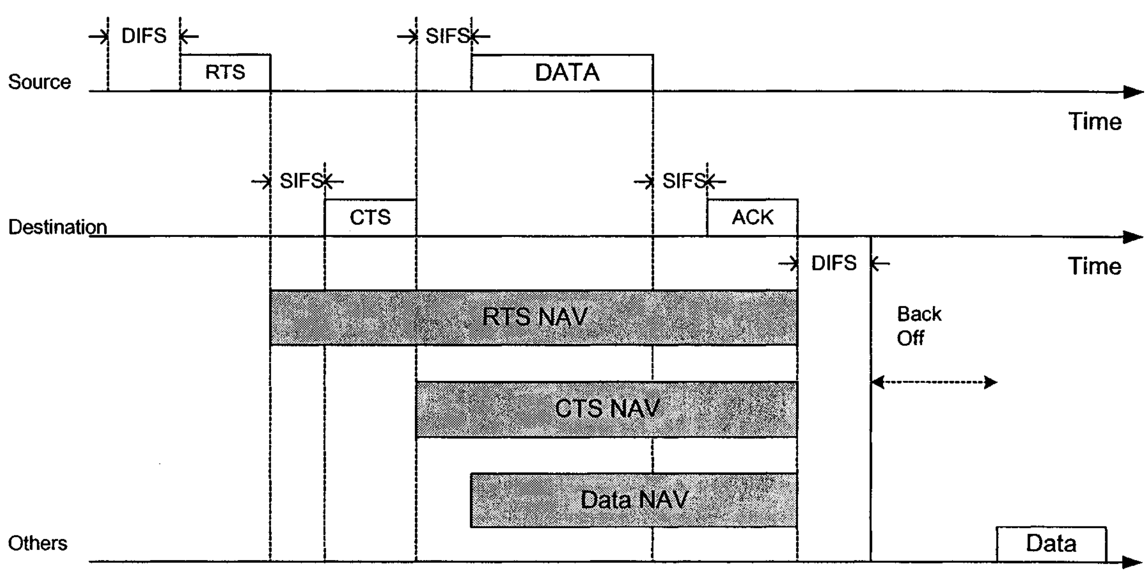


Figure 2. 5: DCF Virtual Carrier Sense Protocol

As discussed earlier, after a collision, the source station continues transmitting the complete MPDU because the WLAN uses CSMA/CA, which hinders transmitting stations from detecting collisions. The continuation of transmission when collisions occur results in the wasting of channel bandwidth, where more is wasted as the frame size increases. Transmitting the RTS and CTS frames reduces collisions by reserving the channel and minimizing the amount of wasted bandwidth when collisions occur (due to the small size of RTS and CTS control frames, 20 and 14 octets, respectively, verses data frames of a maximum size of 2346 octets).

Another mechanism used to reduce wasted bandwidth after a collision, and to increase the transmission reliability, is the use of fragmentation and reassembly. MAC Service Data Unit (MSDUs) of size larger than the manageable parameter Fragmentation_Threshold, handed down from LLC to MAC, may require fragmentation. MSDU is fragmented into multiple MPDUs of size equal to Fragmentation_Threshold with the exception of the last MPDU, which is of variable size not to exceed Fragmentation_Threshold. Figure 2. 6 shows a MSDU fragmented into several MPDUs. Fragmenting a large MSDU into smaller MPDUs reduces the wasted bandwidth after a collision and in retransmitting packets previously corrupted by noise in the medium. Also, due to the high bit error rate of a radio link, the probability of a packet being corrupted increases with the packet size.

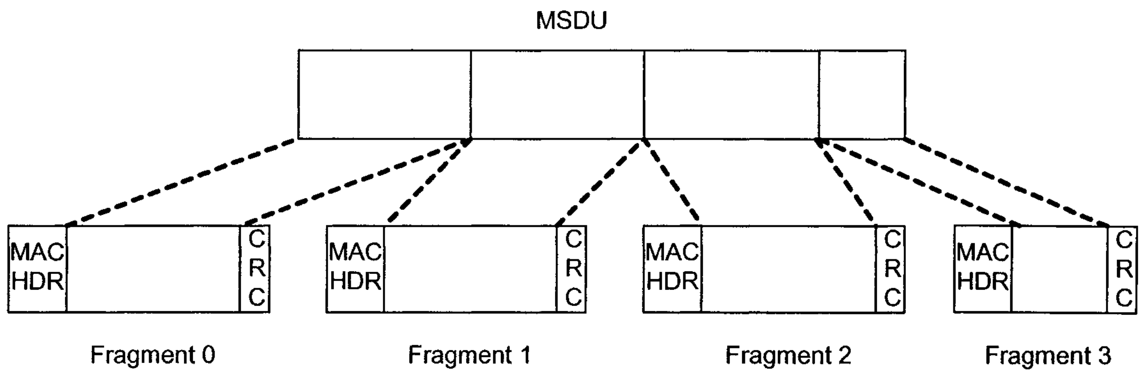


Figure 2. 6: Fragmentation of a MSDU

If a MSDU is being fragmented, the fragments are transmitted sequentially using a simple send and wait algorithm. The channel is not released until the complete MSDU has been transmitted successfully, or the source station fails to receive an acknowledgment for a transmitted fragment. The source station transmits each fragment after SIFS period from receiving the ACK of the previously transmitted fragment. The destination station positively acknowledges each of the received fragments. In the case that the source station does not receive an ACK (Figure 2. 7), it stops transmitting and contends again for the channel. Once the source station gains access to the channel, it starts transmitting with the last unacknowledged fragment. Figure 2. 7 illustrates a missed acknowledgment and Figure 2. 8 illustrates the sequential transmission of multiple fragmented MSDUs using the send and wait algorithm.

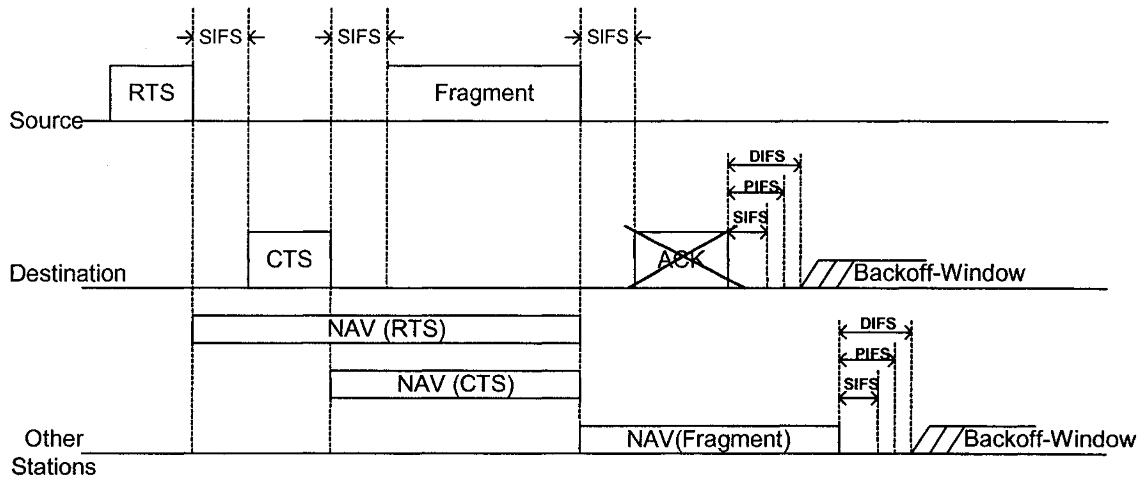


Figure 2. 7: Missed ACK While Transmitting Fragmented MSDU

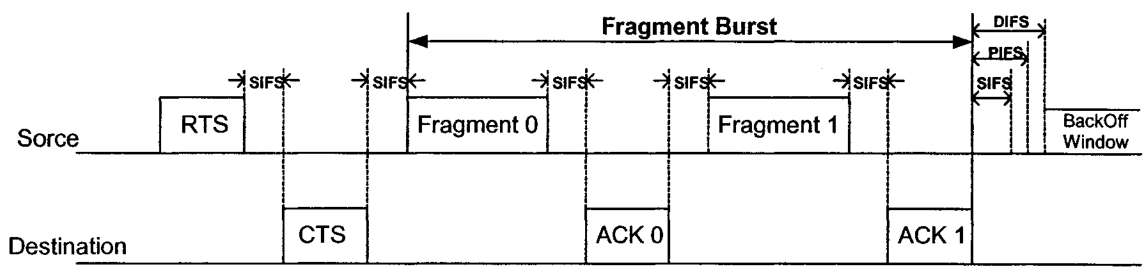


Figure 2. 8: Sequential Transmission of Fragmented MSDU Using RTS/CTS

If control frames RTS and CTS are used, the handshaking mechanism will be used for transmitting only the first fragment. This means that the value in the duration field of the RTS and CTS only defines the duration of the first fragment and its acknowledgment. The value of the duration field of the fragments and the ACK frames specifies the total duration of the next fragment and acknowledgment. Each frame contains information defining the duration of the next transmission. Refer to Figure 2. 8 above for an illustration of transmitting fragmented MSDU using RTS/CTS. The destination station uses the information provided in the header of each fragment to reassemble the MPDU.

2.1.2.2 Point Coordination Function

The PCF is an optional capability offered by the IEEE 802.11 to provide support for time-bounded services [4]. A station performing PCF traffic management is called a point coordinator (PC). The function of the PC is to perform polling, which enables the polled station to transmit without contending for the channel. The AP within each BSS performs the function of the PC. Since PCF is optional, not all stations will be capable of operating during the CFP. Stations that are able to respond to CF-Polls during the CFP are known as CF-Aware stations. The method determined by the PC for choosing the polling stations is not specified in the standard and is left to the implementers.

The CFP will alternate with a CP according to the CFP repetition interval, which determines the frequency with which the PCF occurs. The PC generates CFP period at the contention-free repetition rate (CFP_Rate). The sum of the two periods is called a superframe. It may happen that a station begins transmitting a frame just before the end of the CP, thus elongating the current superframe and shortening the next one, as shown in Figure 2. 9.

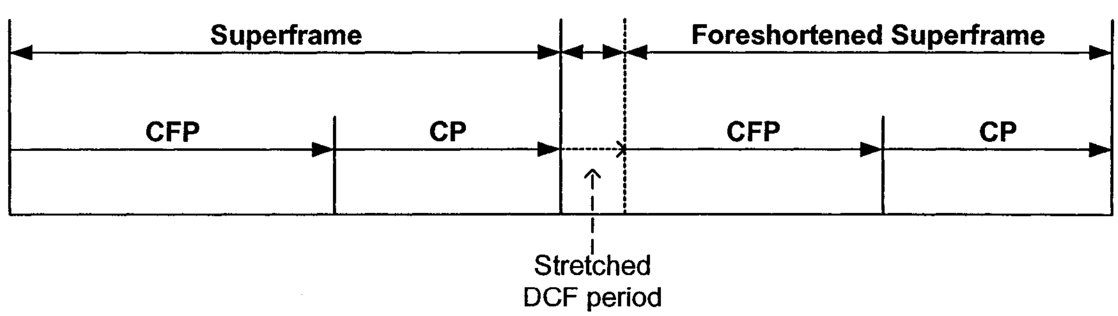


Figure 2. 9: Superframe and Stretched DCF Period

At the start of the CFP and after the PC senses that the channel is idle for a PIFS interval, the PC transmits a beacon frame to gain control of the channel. The beacon frame contains a Delivery Traffic Indication Message (DTIM) element, used for synchronization and timing. If the traffic during the CFP is light or the PC has completed polling all the stations on the polling list, the PC can end the CFP by transmitting a CF-End frame. Figure 2. 10 shows how CFP alternates with CP in a superframe structure as well as the NAV setting of the IEEE 802.11 WLAN stations.

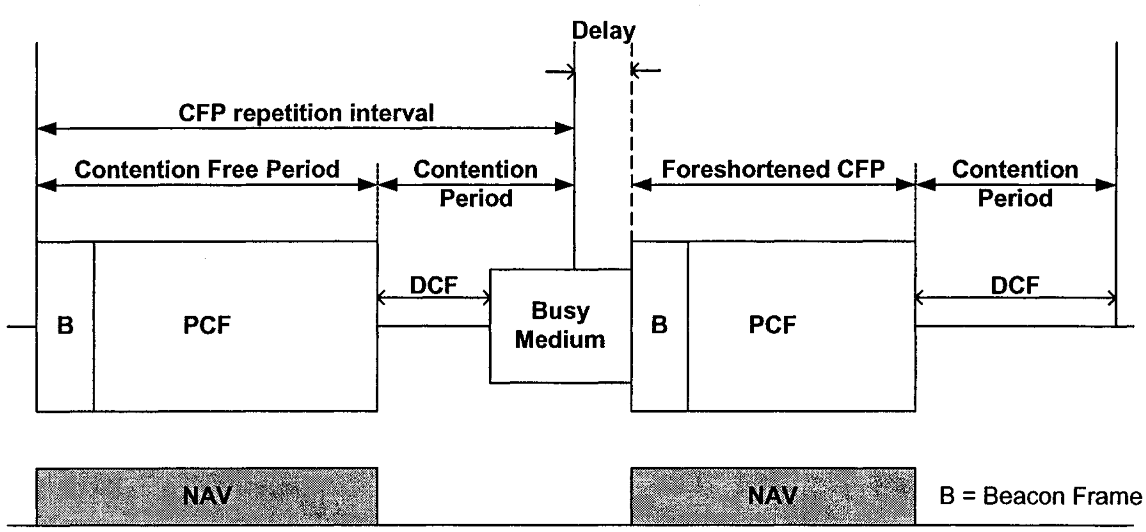


Figure 2. 10: Coexistence of the PCF and DCF

The length of the CFP is a manageable parameter controlled by the PC, with a maximum size controlled by the manageable parameter CFP_Max_Duration. The minimum value that the CFP_Max_Duration parameter can have is the time required to transmit two maximum size MPDUs, including overhead, the initial Beacon frame, and a CF-END frame used to end the CFP. This duration allows sufficient time for the AP to send one data frame to a station, while polling it and allowing the polled station to respond with one data frame. The maximum value that the CFP_Max_Duration can have is the CFP repetition interval minus the time required to successfully transmit a maximum size MPDU, the RTS/CTS handshaking and the ACK packet during the CP.

After the PC gains control over the channel, all stations in the BSS update their NAV to the maximum length of the CFP (CFP_Max_Duration). The PC waits for a SIFS period then transmits one of the following frames: CF-Poll (no data), Data, or Data+CF-Poll frame. During CFP, stations are only permitted to transmit in response to a poll from the PC or for transmission of an acknowledgment within a SIFS interval after the reception of an MPDU. To avoid the overhead of transmitting an ACK frame only, CF-Aware stations can acknowledge a correctly received data frame by transmitting one of the following frames: Data+CF-ACK, CF-ACK, CF-ACK+CF-Poll or Data+CF-ACK+CF-Poll (where the last two frames are only transmitted by the PC). Non CF-Aware stations respond to a correctly received data frame by an ACK frame only after SIFS interval of time. Figure 2. 11 shows an example of PCF packet transfer.

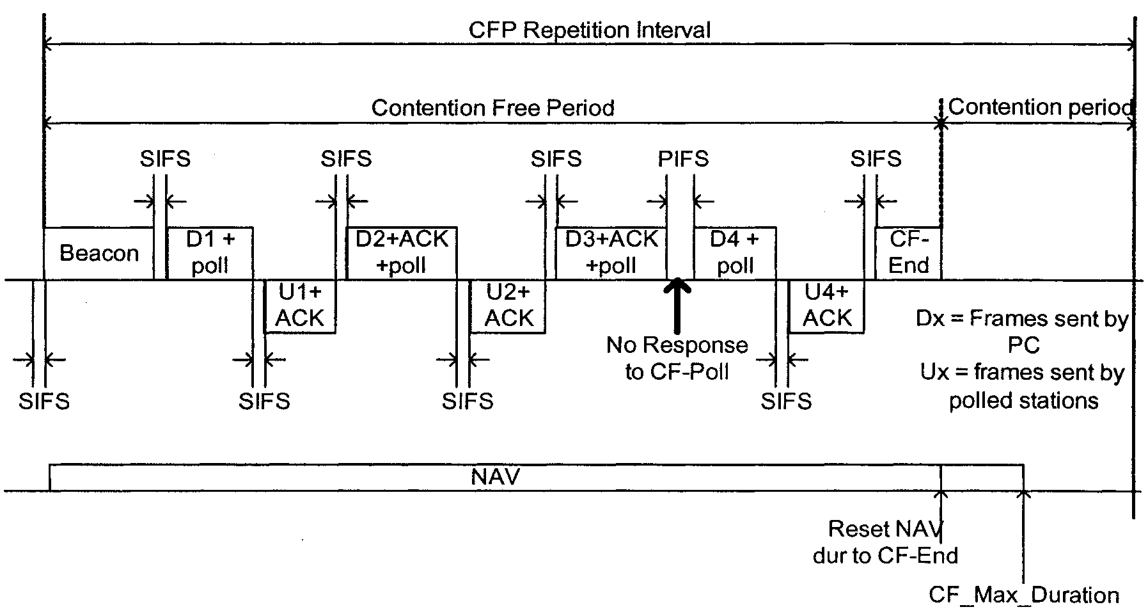


Figure 2. 11: PCF Packet Transfer

2.2 IEEE 802.11 Extensions

The IEEE published the 802.11 standard in 1997, and since that time there has been variant standards and work groups that have been constructed based on the IEEE 802.11 standard. A list with a description of each variant extension that have been developed or being developed at this time is given below [9]:

- **IEEE 802.11a:** This extension was published in 1999 and defines a standard for WLAN operating in the 5 GHz unlicensed band allowing data rate up to 54 Mbps. The IEEE 802.11a extension uses the Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a method that allows transmission of high data rates over extremely hostile channels at a comparable low complexity.
- **IEEE 802.11b:** This extension was published also in 1999 and defines a standard for WLAN operating in the 2.4 GHz band with data rates of up to 11 Mbps. IEEE 802.11b is also known as Wireless Fidelity (Wi-Fi) and defines the High Rate Direct Sequence Spread Spectrum (HR/DSSS) transmission mode with a chip rate of 11 Mchip/s. DSSS is elaborated upon in Appendix A.
- **IEEE 802.11c:** Without any additional development, this task group provided documentation of IEEE 802.11-specific MAC procedures to the ISO/ International Electrotechnical Commission (IEC) 10038.
- **IEEE 802.11d:** Published protocols and procedures permitting the IEEE 802.11 standard to operate in countries that were not currently utilizing this

standard since the use of the frequency spectrum is different from one nation to another.

- **IEEE 802.11e:** The focus of this task group is to enhance the QoS of the IEEE 802.11 MAC sub-layer. This thesis focuses on this extension.
- **IEEE 802.11f:** Defined the Inter AP Protocol (IAPP) that increases compatibility between AP devices from different vendors.
- **IEEE 802.11g:** The IEEE 802.11g will utilize OFDM similar to the IEEE 802.11a and operate in the 2.4 GHz like the IEEE 802.11b. The usage of OFDM allows the IEEE 802.11g to combine the advantage of IEEE 802.11a (higher throughputs) and IEEE 802.11b (relatively large coverage). The IEEE 802.11g stations will be able to coexist with 802.11b networks striving to achieve a data rate of at least 20 Mbps.
- **IEEE 802.11h:** This extension provides mechanisms for Dynamic Frequency Selection (DFS) and Transmitter Power Control (TPC) that may be used to satisfy European regulations for operation in the 5 GHz band.
- **IEEE 802.11i:** The main focus of this task group is to enhance security and authentication mechanisms of the IEEE 802.11 standard.

2.3 Synopsis of Chapter 2

There are two types of wireless network architecture, the IBSS and the BSS. Multiple BSSs connected through a DS form an ESS. The IBSS, referred to as an ad-hoc network, is formed without the requirement for preplanning; stations communicate directly with each other. The BSS is controlled by a coordination function. The IEEE 802.11 defines two kinds of coordination functions namely the mandatory DCF and the optional PCF. During the DCF, stations have to contend for the channel, while during the PCF, channel access is controlled by a PC by polling stations for transmission. The IEEE 802.11 has different work groups to define extensions that will enhance the standard. Among them is the IEEE 802.11e workgroup to enhance the QoS of the standard. Chapter 3 discusses extension “e” in more details since it is the main focus of this thesis.

Chapter 3

IEEE 802.11e to Enhance WLAN QoS

The IEEE 802.11 has QoS limitations that prevents its use in real-time applications such as VoIP, video streaming and videoconferencing. Techniques applied to improve QoS of the wired networks do not translate to the WLAN [10]. This is because of the high error rate of the wireless medium and the variation of bit rate according to the channel conditions. New techniques specific to the IEEE 802.11 must be implemented to prioritize voice and video packets over data packets and to utilize the channel efficiently. In this Chapter the IEEE QoS limitations are listed as well as an explanation of the upcoming IEEE 802.11e standard and other techniques in the literature for improving WLAN QoS.

3.1 IEEE 802.11 QoS Limitations

In Chapter 2 it was explained that the IEEE 802.11 MAC protocol support two access mechanisms: the mandatory DCF and the optional PCF. The DCF works as a listen-before-talk scheme based on CSMA/CA, whereas the PCF allows a point coordinate to have control over the wireless medium by polling each station for data. Both mechanisms have their own QoS limitations [11].

DCF does not provide any QoS guarantees; rather it provides a best effort service with a single First In First Out (FIFO) transmission queue. During DCF, all stations in the same BSS compete to access the wireless medium. All stations have the same priority with no differentiation mechanism guaranteeing the bandwidth, packet delay or jitter for high priority stations (those with real-time or multimedia traffic). With the increase in the number of stations in a BSS, the data drop rate, delay and jitter increase dramatically. In IEEE 802.11e, the DCF is enhanced to provide traffic prioritization.

The PCF access mechanism is designed to support time-bounded services, but it has some QoS weaknesses such as:

- The beacon transmission time to start the CFP can be delayed due to the incompatible cooperation between the CP and CFP modes. At the Target Beacon Transition Time (TBTT) [4], the PC schedules the beacon as the next frame to be transmitted. The transmission of the beacon is not achieved except when the medium becomes idle for PIFS period of time. A delay in the beacon transmission occurs because stations can start transmission even if they cannot finish before the coming TBTT. The simulation of the PCF performed in [12] shows that the average beacon frame delays can be up to 250 μs depending on frame lengths, fragmentation, and the offered traffic as shown in Figure 3. 1 [12]. This limitation is remedied in the IEEE 802.11e such that the station does not transmit if the transmission will exceed the upcoming TBTT.

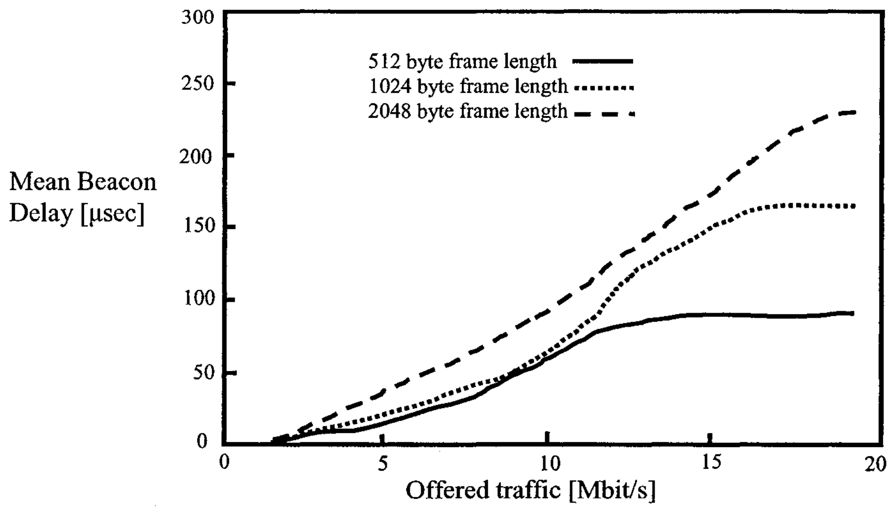


Figure 3. 1: Mean Beacon Frame Delay in IEEE 802.11

- The transmission time of a polled station is unpredictable [11]. A polled station may transmit a frame of arbitrary length up to 2304 bytes and it could be fragmented. Depending on the PHY transmission rate, the transmission time can be very long, which prevents providing any QoS to the other stations polled during the rest of the CFP. This limitation is solved in the upcoming IEEE 802.11e standard by introducing the concept of transmission limit, explained in the next section.

3.2 *IEEE 802.11e Extension to Improve QoS*

It was mentioned earlier that the WLAN IEEE 802.11 standard has QoS limitations. Because of these limitations, the IEEE 802.11 Task Group E (TGe) was formed to define enhancements for the legacy IEEE 802.11 MAC. In this subsection a detailed explanation of the IEEE 802.11e draft [13] is presented. Understanding the draft is important since this thesis evaluates the QoS performance of the IEEE 802.11e.

In the IEEE 802.11e draft and within this thesis, a station or an AP that implements the QoS facility described in the draft is referred to as a QoS Station (QSTA) or a QoS AP (QAP) respectively. The function of a QAP is inclusive of the functions of an AP, thus QAP can function as an AP to non-QSTA. Also, a BSS that provides the QoS facilities is referred to as QBSS. A QSTA acts as a non-QoS STA when associated with a non-QoS BSS [13].

The IEEE 802.11e defines a new point coordinator method called Hybrid Coordination Function (HCF). The HCF is composed of two access mechanisms: the Enhanced Distributed Coordination Function (EDCF) and the HCF controlled channel access mechanism. The EDCF is used to operate in the CP only, while the HCF controlled channel access is used in both phases. This is why the HCF is known as Hybrid. A QSTA may obtain Transmission Opportunity (TXOP) using one of the HCF channel access mechanisms. TXOP is an interval of time (defined by a starting time and a maximum duration) by which a particular QSTA has the right to initiate transmission onto the wireless medium [13].

3.2.1 Enhanced Distributed Coordination Function (EDCF)

IEEE 802.11e supports the concept of prioritizing and differentiating frames with up to eight priority levels of traffic that map directly to wired network protocols. A STA accesses the channel based on the Access Category (AC) of the frame that is to be transmitted. A non-QSTA will have an AC of zero, but for QSTA, each frame will have an AC derived from its priority value as it is received from the higher level. See Table 3. 1 for priority mapping [13].

Table 3. 1
Mapping of each priority to an AC

Priority (Same as 802.1D bridge specification priority)	Access Category (AC)	Designation (Informative)
1	0	Best Effort
2	0	Best Effort
0	0	Best Effort
3	1	Video Probe
4	2	Video
5	2	Video
6	3	Voice
7	3	Voice

The frame is stored in the transmit queue of the AC to which the frame's priority is mapped. Each AC acts as an enhanced variant of the DCF. Therefore, within a QSTA, each AC contends for a TXOP using its own QoS EDCF parameters specifically for that AC. The different values used for each AC allows the prioritization of an AC over another. These parameters include CW_{min}[AC], CW_{max}[AC], Arbitration Inter Frame Spacing (AIFS[AC]). AIFS[AC] is at least equal to the DIFS and can be enlarged individually for each AC and AIFS Number AIFSN[AC]. The channel access function is a logical function that determines when a frame in the transmit queue with the associated AC is permitted to be transmitted via the wireless medium. Figure 3. 2 shows the reference implementation model [13].

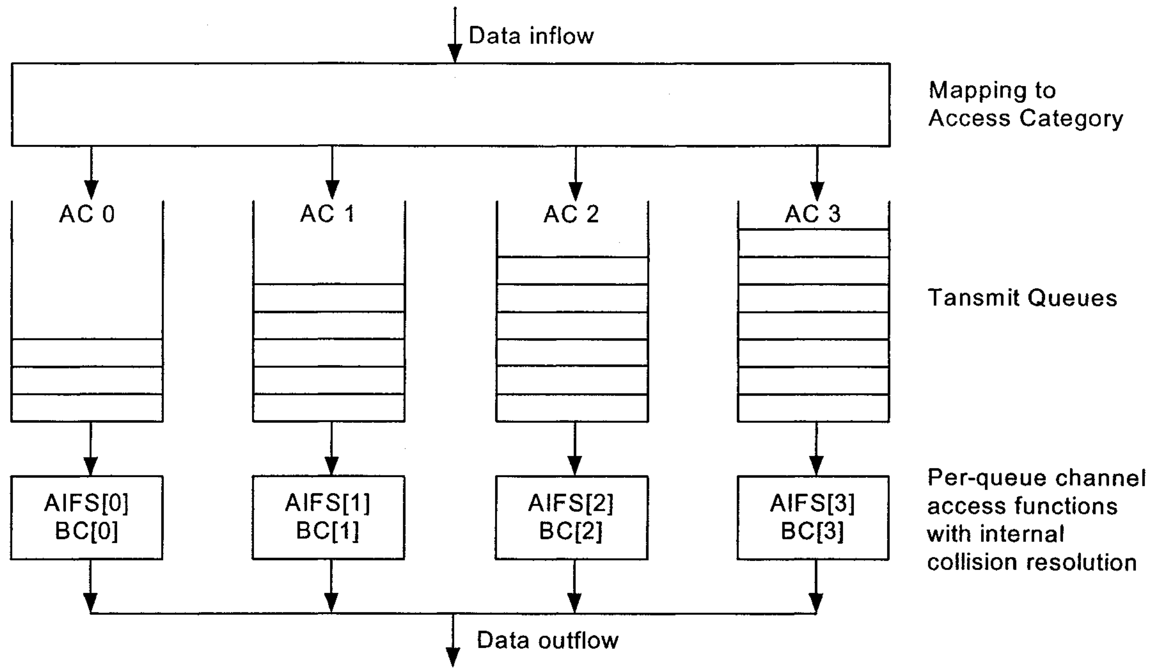


Figure 3. 2: Reference Implementation Model

Similar to DCF, each station senses the medium and defer from transmitting if the medium was found busy. A different back-off counter is used for each access category within a QSTA. The back-off counter is a random number from the interval [1, CW(AC)+1], where CW(AC) is initially assigned the value $CW_{min}(AC)$, and increases with every unsuccessful transmission attempt up to $CW_{max}(AC)$. Prioritization or channel access differentiation can be achieved by assigning low values for $CW_{min}(AC)$, and $CW_{max}(AC)$ for high priority traffic. After each successful transmission, the CW(AC) is reset to $CW_{min}(AC)$.

When the QSTA senses that the medium has become idle, each channel access function defers for a period of AIFS(AC) before starting the back-off window. AIFS(AC) is calculated using the formula [13]:

$$AIFS[AC] = AIFSN[AC] \times aSlotTime + aSIFSTime$$

After the AIFS(AC) elapse, as long as the medium is still idle, the back-off counter starts to decrement. Virtual collision happens when the back-off counter of two or more access functions within a single QSTA reaches zero simultaneously. The TXOP is granted to the highest collided priority traffic. The timing diagram of the EDCF is shown in Figure 3. 3 [13].

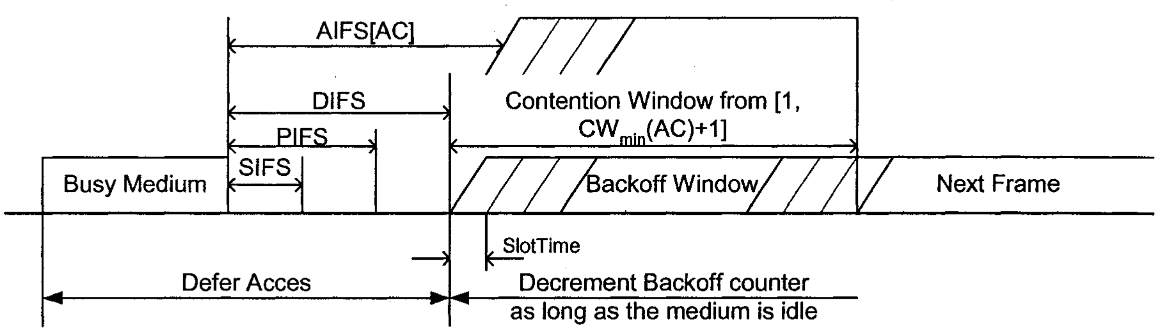


Figure 3. 3: EDCF channel access timing diagram

To prevent one station from utilizing the medium for a long period of time, the IEEE 802.11e introduces the concept of TXOPLimit[AC], by which the station that receives the TXOP for a specific AC is allowed to transmit for the interval of TXOPLimit(AC). QSTA can transmit multiple MPDUs from the same AC with a SIFS time gap between an ACK and the subsequent frame transmission. The total transmission time for all frames, with the total SIFS interval in between the frames, should be less than the interval TXOPLimit(AC). Figure 3. 4 shows the transmission of multiple data from the same AC in the TXOPLimit(AC).

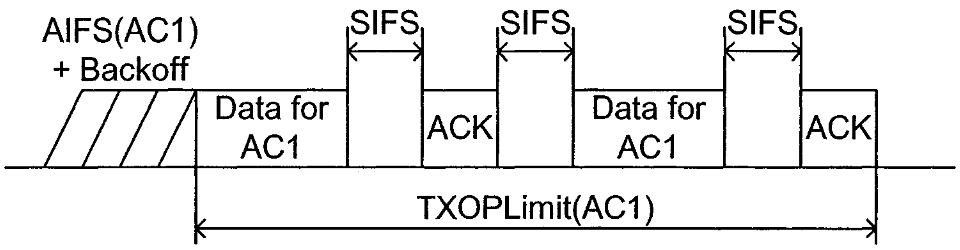


Figure 3. 4: Multiple Frame transmission during TXOPLimit

3.2.2 HCF Controlled Channel Access Mechanism

The HCF mechanism uses a QoS aware point coordinator, called a Hybrid Coordinator (HC) to access the Wireless Medium (WM). The HC has higher medium access priority than non-AP QSTAs. This allows it to transfer traffic from itself, and to allocate TXOPs to non-AP QSTAs. HCs are colocated with QAP and operate under different rules from the PC used in IEEE 802.11 PCF. The HCF mechanism for controlling channel access mechanism is based on a polling mechanism similar to PCF. All QSTAs are able to respond to QoS CF-Polls received from an HC [13].

The HC may also operate as a PC, providing non-QoS CF-Polls (as specified in the PCF). The HCF controlled channel access mechanism can be used during both the CP and the CFP. The HC starts the contention free period during contention periods referred to as Controlled Access Period (CAP) if the medium is idle for PIFS interval of time. The CAP interval is controlled by the dot11CAPLimit that specifies the maximum number of Time Units (TU) a CAP may last, where a TU is equal to 1024μs [4]. Figure 3. 5 shows the superframe containing CFP, CP and CAP periods.

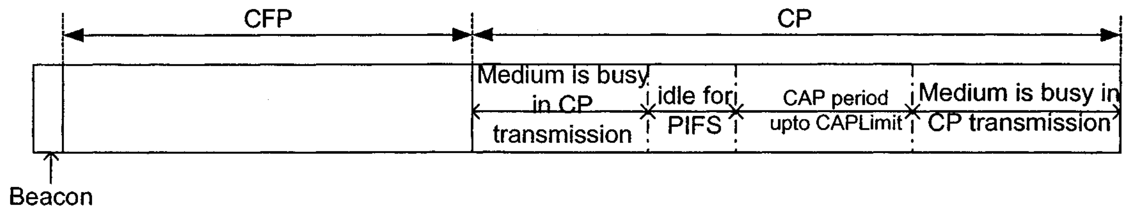


Figure 3. 5: Having CAP during CP

The HC gives a TXOP to a QSTA by polling it using a QoS CF-Poll. The HC also specifies the maximum duration (TXOPLimit) which the polled station is allowed to utilize the wireless medium. The polled QSTA (TXOP holder) must respond with data after a SIFS period of time from receiving the poll. If the polled QSTA did not respond, then the HC will take control over the wireless medium after a PIFS period of time. The polled station is allowed to transmit multiple MSDUs as long as it is within the TXOPLimit, specified in the QoS CF-Poll. To avoid collisions, other stations in the same BSS set their NAV to TXOPLimit plus a Slot_Time. This extra Slot_Time will allow the HC to initiate a subsequent TXOP with reduced risk of collision. This is because STAs, other than the TXOP holder and the HC, cannot begin contending until a DIFS interval from the end of the last transfer within the TXOP. Figure 3. 6 shows the timing diagram of a polled TXOP [13].

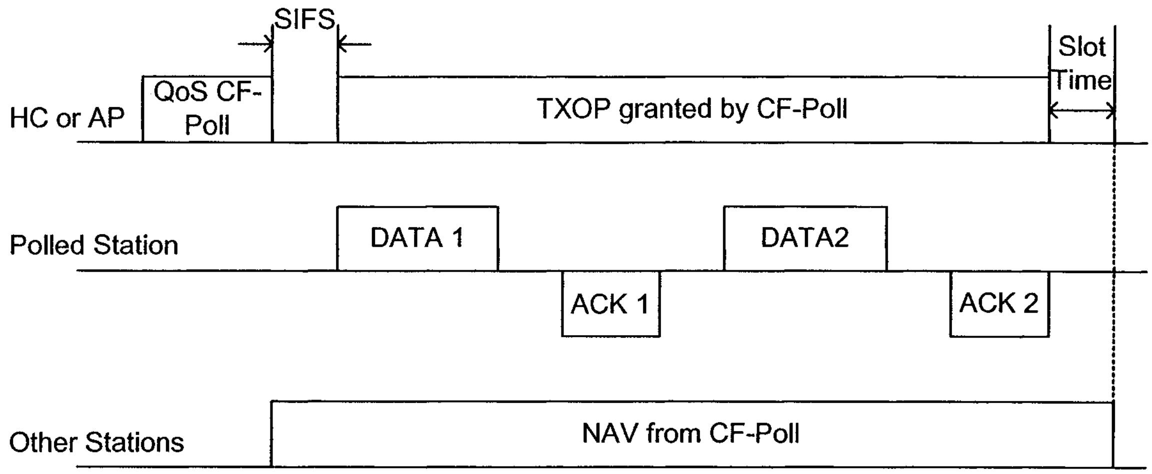


Figure 3. 6: Polled TXOP timing diagram

There are other features defined in the IEEE 802.11e not directly related to the QoS but exist to increase the efficiency of the IEEE 802.11 network. The new features include Block Acknowledgment (Block Ack) and Direct Link Protocol (DLP). The Block Ack mechanism allows multiple QoS data MPSUs to be transmitted separated by a SIFS period, and then a single GroupAck frame acknowledges the group of QoS data frames. Using this approach improves the channel efficiency by grouping several acknowledgements into one frame. DLP is used to allow QSTA within an infrastructure BSS to transmit frames directly to another QSTA instead of the AP relaying the frames. The direct link is established after a handshake between the two QSTAs and the QAP. Figure 3. 7 shows the handshake used to establish DLP [13].

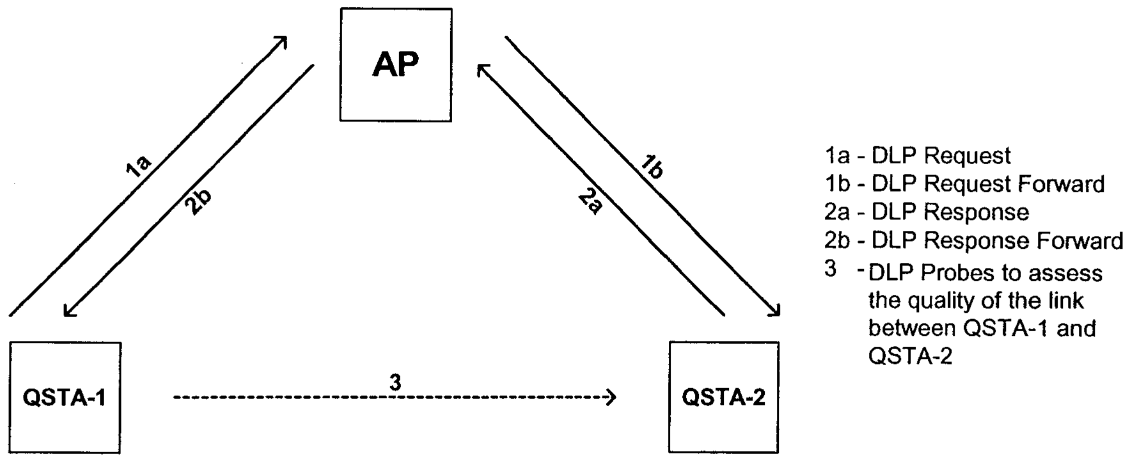


Figure 3. 7: Direct Link Protocol Handshake

3.3 Other Techniques provided to enhance 802.11 MAC

In the past few years, different researches and efforts have been made to improve the WLAN QoS. In this subsection, an overview of some techniques, available in the literature, is presented.

Aad et Castelluccia [14] is based on the IEEE 802.11 standard. The differentiation and prioritization is station based, i.e. the station with traffic requiring high QoS (such as real-time traffic) is considered as a high priority station. High priority stations use smaller CW, DIFS and backoff sizes compared to low priority stations. Also, the maximum frame length that a station is allowed to transmit at once is relative to the priority level of the station. The experimental results show that this technique performs better with UDP traffic rather than TCP traffic because the TCP ACKs affect the differentiation mechanism.

The Black Burst method presented in [15] is aimed to improve the QoS for high priority stations by improving the end-to-end delay. High priority stations contend to access the channel after being idle for medium inter-frame spacing of length t_{med}, which is analogous to the PIFS period of time in the IEEE 802.11 standard. While low priority stations content the channel only after being idle for t_{long}, which is analogous to the DIFS period of time. Hence high priority stations will access the medium before low-priority stations. After the medium becomes idle for t_{med} period of time, each high priority station will jam the channel with pulses of energy referred to as BBs. The pulse length is proportional to the contention delay experienced by the station measured from the instant when the station schedules an attempt to access the channel until the channel becomes idle for t_{med} (which is the start of the transmission of the BB). Each high priority station senses the channel for observation period t_{obs} to determine whether it had the longest BB. The station with the longest BB starts transmitting its frame and schedules the next transmission attempt to t_{sch} in the future, where t_{sch} is the same for all stations. Stations that did not have the longest BB must wait for the channel to become idle for t_{med} period of time and then content for the channel by jamming it with a BB pulse. The mechanism makes the high priority stations appear to access in a dynamic Time Division Multiplexing (TDM) transmission structure without explicit slot assignment or slot synchronization. Simulation showed that the black burst method can handle more real-time (high-priority) stations than CSMA/CA because it reduces the contention overhead. Also the black burst method offers lower delay and jitter than CSMA/CA. The weakness of the black burst method is that hidden terminal may not sense the BB pulse.

[16] proposed a technique called Busy Tone Priority Scheduling (BTPS) that overcomes the hidden terminal problem in an ad-hoc networks (which is the deficiency of black burst method). The BTPS method works as follows. High priority stations transmit

busy tone signals BT1 each M slots (where M is a parameter of the proposed scheme) during DIFS and backoff period. The backoff counter will keep on decrementing as long as the medium is idle. The station with the backoff counter that reaches zero will jam the channel with black burst for two Slot_Time, followed by an RTS packet. The black burst signal will prevent other high priority stations from transmitting busy tones. After getting the CTS reply, the data packet will be sent followed by the ACK. To solve the hidden terminal problem, stations receiving BT1 will transmit another busy tone signal BT2. Consider Figure 3. 8 where Station 0 is a high priority station with traffic to Station 1. Station 2 is a low priority station with traffic to Station 1. Station 0 and Station 2 do not see each other (hidden terminal problem). Station 0 will transmit BT1 to which station 1 will hear but not Station 2. Station 1 will in turn transmit BT2, which when received by Station 2, will refrain this station from transmitting because it is a low priority station. Hence stations will be aware of hidden high priority stations.

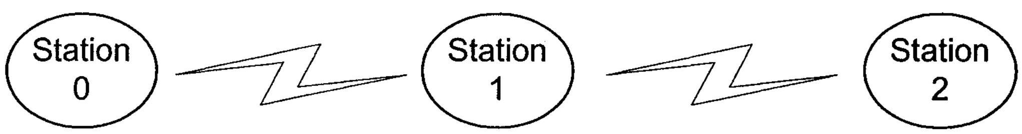


Figure 3. 8: Hidden terminal problem with BTPS

3.3 Synopsis of Chapter 3

The upcoming IEEE 802.11e draft to enhance the QoS defines a new coordinate function known as HCF. This coordinate function is composed of EDCF and HCF controlled access mechanisms. The EDCF is based on the DCF defined in the IEEE 802.11 standard, but provides four transmission queues as opposed to one. The four queues of the IEEE 802.11e are used to provide a prioritization mechanism for the stations' traffic. Frames are queued based on their priorities, which are mapped to the access category. Each queue is assigned a specific AC. Queues have an access function to determine when to transmit. Different values for CW_{min}, CW_{max} and AIFSN, used by each access function, will provide traffic prioritization. The HC controlled channel access mechanism is similar to the PCF defined in IEEE 802.11. A major enhancement is having CAP during contention free periods, thereby increasing the efficiency of the channel efficiency. Transmitting stations are referred to as TXOP holder, and are allowed to transmit for TXOPLimit.

In the literature there are various techniques, similar to the IEEE 802.11e, to improve the WLAN QoS. Yet the focus of this thesis is to evaluate the upcoming IEEE 802.11e. The simulation (by which this draft is assessed for effectiveness to enhance the QoS) and results are presented in the next chapter.

Chapter 4

Simulation Results and Analysis

To evaluate the QoS performance of the IEEE 802.11e by simulation, the Optimized Network Engineering Tools (OPNET) [17] was used to model the draft and the traffic sources. In this chapter the model description will be presented along with the scenarios used and analysis of the obtained results.

4.1 Traffic Model

During the scope of this study, the performance of the IEEE 802.11e draft was evaluated under three types of traffic: voice, video and data traffic. Each wireless node could generate traffic from the three sources simultaneously. Voice and video traffic are delay sensitive but tolerant to some frame losses, while data traffic is delay insensitive and intolerant to frame losses. The voice traffic source has a data rate of 0.0368 Mbps, while the video and data traffic sources have data rates of 1.4 and 1.0 Mbps, respectively. Table 4. 1 summarizes the traffic source characteristics [12, 18]. Voice traffic is referred to as high priority traffic, while video and data traffic are referred to as medium and low priority traffic, respectively.

Table 4. 1
Traffic Source Characteristics

Traffic Type	Inter arrival Time (Seconds)	Packet Size (bytes)	Data Rate (Mbps)
Data	Exponential (0.012)	1500	1.0
Video	Constant (0.001)	1464	1.4
Voice	Constant (0.02)	92	0.0368

4.2 Simulation Assumptions

Certain assumptions were taken during the scope of this project; following is the list of the assumptions:

- In all the scenarios, location and distances of the stations were chosen to avoid having hidden nodes. Therefore, all stations were in the transmission range of each other.
- The TXOPLimit of each AC was assumed as the time it takes to transmit one packet for that AC.
- The direct link protocol (DLP) defined in the draft (explained briefly in Chapter 3) was out of the scope of this study as DLP increases the efficiency of WLANs and does not negatively impact QoS.
- The video probe corresponding to AC 1 (refer to Table 3. 1 in Chapter 3) was not modelled, so the simulation scope considered only voice, video and data. Accordingly, each wireless station had only three transmission queues instead of four.

4.3 IEEE 802.11e Model Design

OPNET's libraries and models [17] were used and extended to design the IEEE 802.11e model [13]. Each wireless station was assigned three transmission queues; one for each traffic source: voice, video and data traffic. Also, each station had the implementation of the three traffic sources [12, 18] and can be configured to transmit any combination of high, medium and low priority traffic simultaneously. The sizes of the CW_{min} and CW_{max} for each AC are external attributes that can be changed from the model attribute window. The IEEE 802.11e node model is shown in **Error! Reference source not found.** [17]. The window to change the attributes of the model is shown in Figure 4. 2

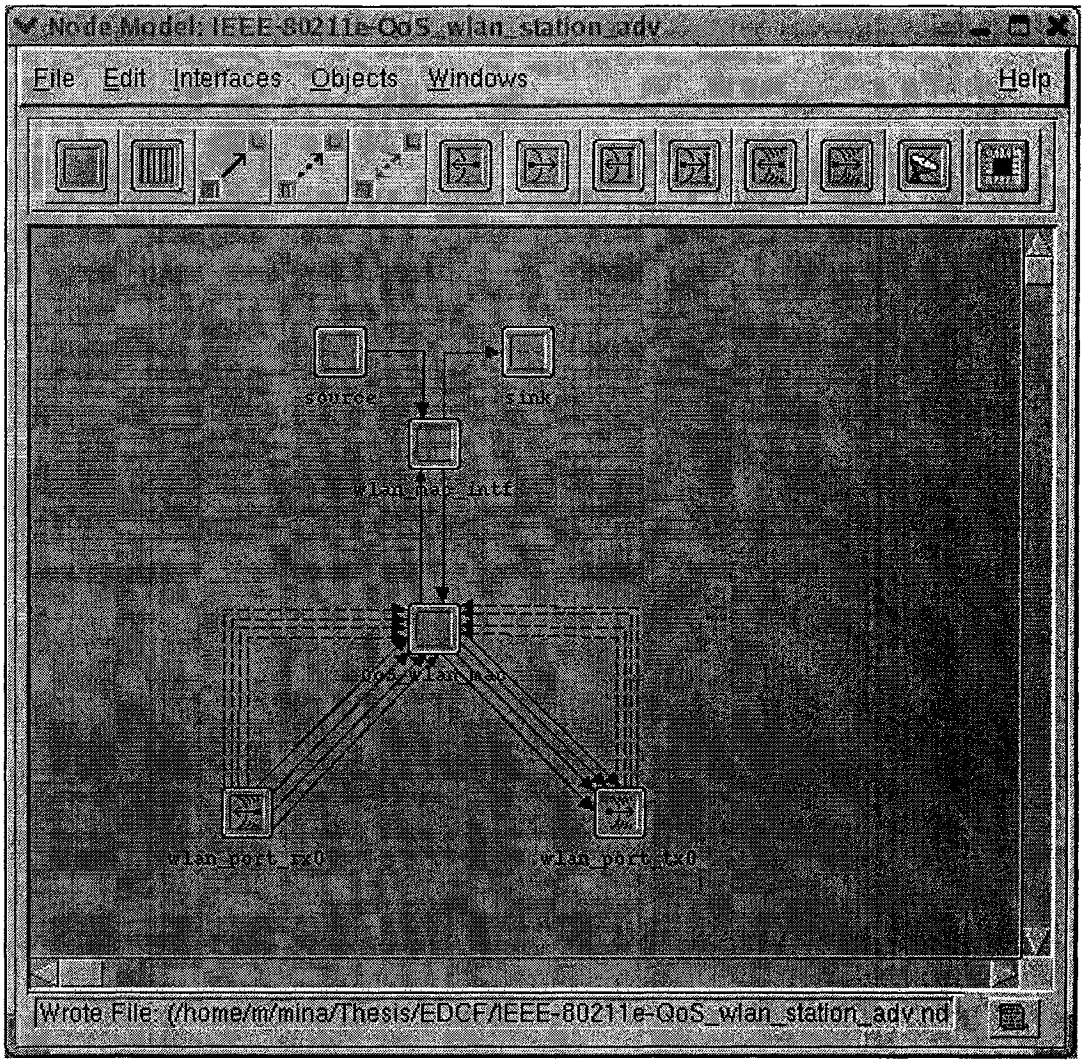


Figure 4. 1: IEEE 802.11e node model

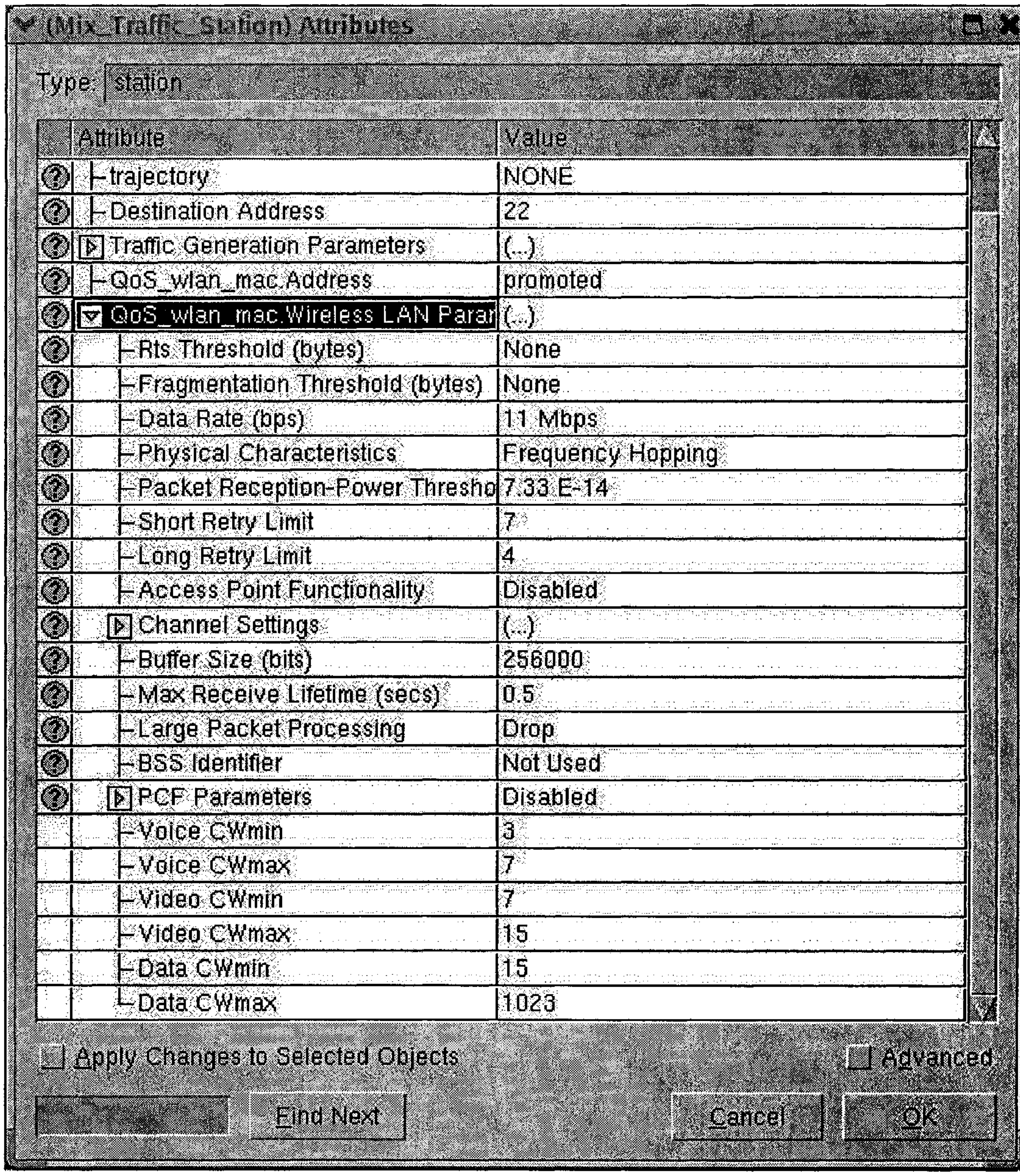


Figure 4. 2: Model Attributes

The developed IEEE 802.11e model collects two levels of statistics:

1. *Local wireless node level of statistics:* These are statistics related to each individual node in the simulated network. To list a few:

   - Amount of data and control traffic sent and received by each individual wireless station.
   - End-to-end delay for packets received by each wireless station.

- Throughput for each station.

Each statistic is gathered per traffic category level; for example, end-to-end delay for voice packets received by each station.

2. *Global level statistics:* These are statistics to reflect the overall status of the simulated network. The gathered global statistics are:

   - Delay: This represents the total end-to-end delay in seconds, of all packets per traffic category, received by the MACs of all the wireless nodes in the simulated network.
   - Load: Is the total load, per traffic category, of all nodes in the network in units of bits per seconds (bps).
   - Throughput: Is the total number of bits received by all nodes in the simulated network. The throughput statistic is presented in units of bps.
   - Data Dropped: Is the total data dropped, per traffic category, of all nodes in the simulated network in units of bps.
   - Media Access Delay: Is the total queuing and media contention delays experienced by the packets, per traffic category, received by all stations in the simulated network. The media access delay is presented in units of seconds.

4.4 WLAN Model Configuration

The physical layer of the WLAN model used throughout this study was the 802.11b PHY layer [19] using Frequency Hopping Spread Spectrum (explained in Appendix A), with maximum data rate of 11 Mbps to simulate the wireless medium. The configurations of other WLAN parameters used in this study are summarized in Table 4. 2.

Table 4. 2
Configuration of WLAN

WLAN Parameter	Value
PHY Layer	FHSS
Channel Transmission Rate	11 Mbps
Slot_Time	0.05 ms
SIFS_Time	0.025 ms
DIFS_Time	0.128 ms

4.5 Simulation and Results

To better evaluate and assess the QoS performance of the IEEE 802.11e, the study strategy was divided into different scenarios. Each scenario was simulated and the obtained results were analyzed in order to achieve a meaningful conclusion. The following subsections will explain the utilized simulation scenarios.

4.5.1 Legacy Verses QoS Data Networks

The aim of this scenario is to determine the IEEE 802.11e data network capacity, i.e. what is the performance of the IEEE 802.11e network as the number of data QSTA increases. A comparison was made between the QoS network (network having all QSTAs) and the legacy network (network having non-QSTA, i.e. IEEE 802.11 stations without the implementation of the draft). The metrics of this scenario is the global average network throughput. The values of the IEEE 802.11e parameters used in the data QSTA are CW_{min}= 15 and CW_{max}= 1023. Figure 4. 3 shows the topology used with five wireless data stations. An extra wireless station was added in the simulation runs, where each run began with one station up to fifteen. All data stations are generating data traffic only (refer to Section 4.1).

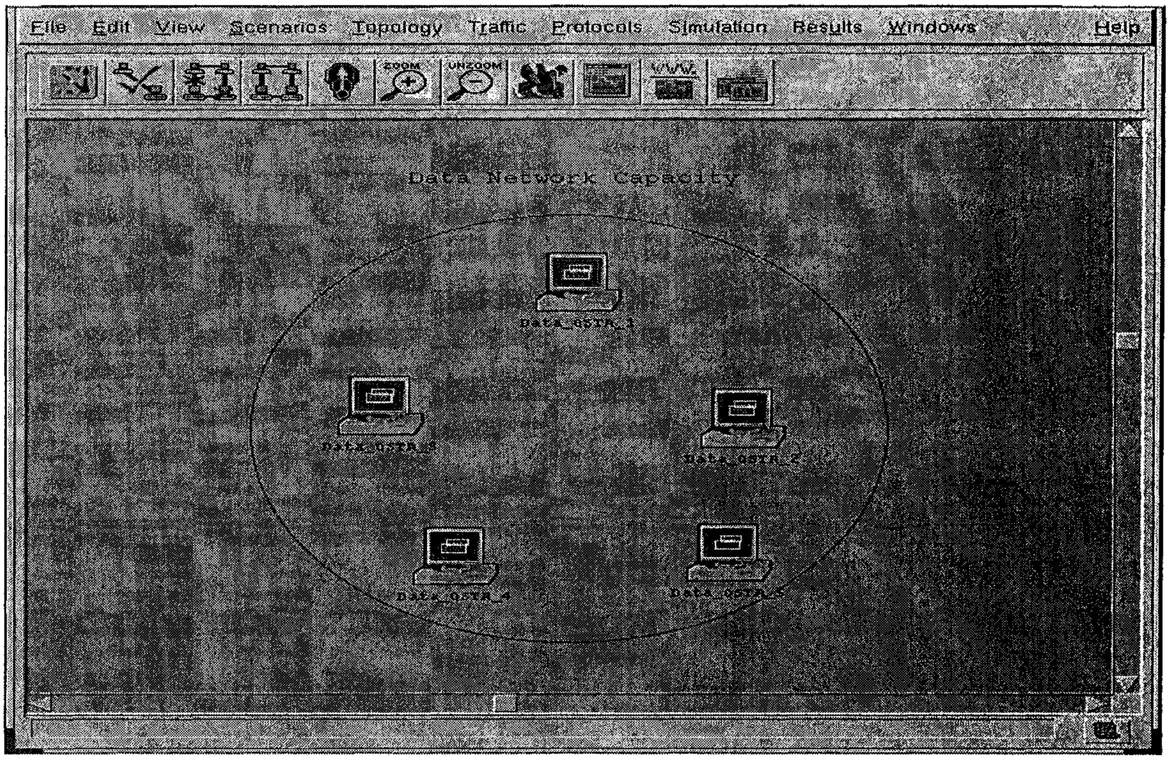


Figure 4. 3: Network Topology Used to Find The Data Network Capacity

As the bar chart in Figure 4. 4 illustrates, the achieved average network throughput is the same for legacy and the QoS network because the values of the CW_{min} and CW_{max} parameters are the same for stations in both networks.

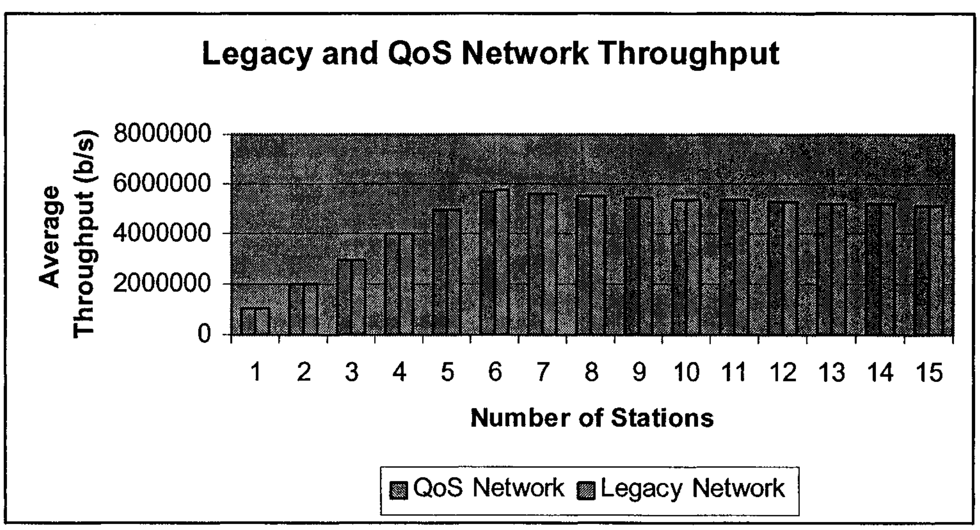


Figure 4. 4: Average Throughput for QoS and Legacy Data Networks

From Figure 4. 4, it can be seen that after the sixth station the graph is not linear and the average throughput decreases, which is due to delays and data being dropped. Therefore, it can be seen that the capacity for the IEEE 802.11e QoS data network is efficient for six stations.

From these obtained results, it can be inferred that networks having data users only (e.g. libraries or warehouses where users are just transferring data traffic) is not needed to be upgraded to the IEEE 802.11e since there will be no gain in the service improvement. This result will save businesses, considering upgrading their WLAN equipment, tremendous amount of money as no performance improvement will be achieved. Also, discovering that the data network has a capacity of six data users can guide businesses while doing their wireless network planning (e.g., wireless networks could be overlapped in order to accommodate and better serve all data users).

4.5.2 Legacy Verses QoS Video Networks

The aim of this scenario is to assess the IEEE 802.11e video network capacity, i.e. what is the performance of the IEEE 802.11e network as the number of video QSTA increases. A comparison was made between the QoS video network and the legacy video network. The metrics of this scenario is the global average network throughput. The value of the IEEE 802.11e parameters used in the video QSTA are CW_{min}= 7 and CW_{max}= 15; these values are specified in the IEEE 802.11e draft. While the values for a legacy video station (non-QSTA) are CW_{min}= 15 and CW_{max}= 1023; these values are defined in the IEEE 802.11 standard to be used by all kinds of traffic. Figure 4. 5 shows the topology used with four wireless video stations. An extra wireless station was added in the simulation runs, where each run began with one station up to fifteen. All video stations are generating video traffic only (refer to Section 4.1).

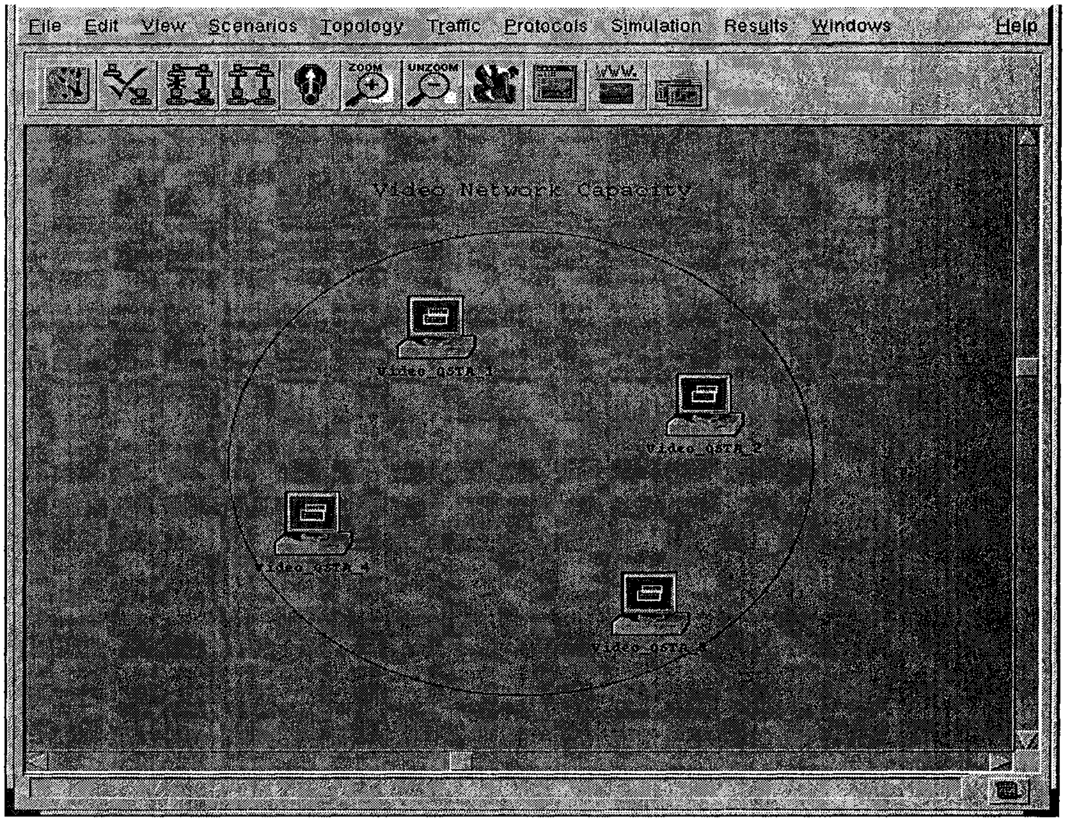


Figure 4. 5: Network Topology Used to Find The Video Network Capacity

The graph in Figure 4. 6 shows the average throughput for legacy and the QoS network. The graph is linear for both networks up to four video stations, after which both curves start to decrease. A steeper decrease is noticed in the curve obtained from the QoS network because the interval from CW_{min} to CW_{max} is smaller in video QSTA compared to the legacy station. As the number of video stations increases, all having to select a random backoff timer from the interval [1,CW(AC)] (where CW(AC) is initially set to CW_{min} and increased to CW_{max}) the smaller the value of CW(AC) the higher the probability that the backoff timer will be the same in two or more stations. Hence collisions occur with a decrease in the average throughput.

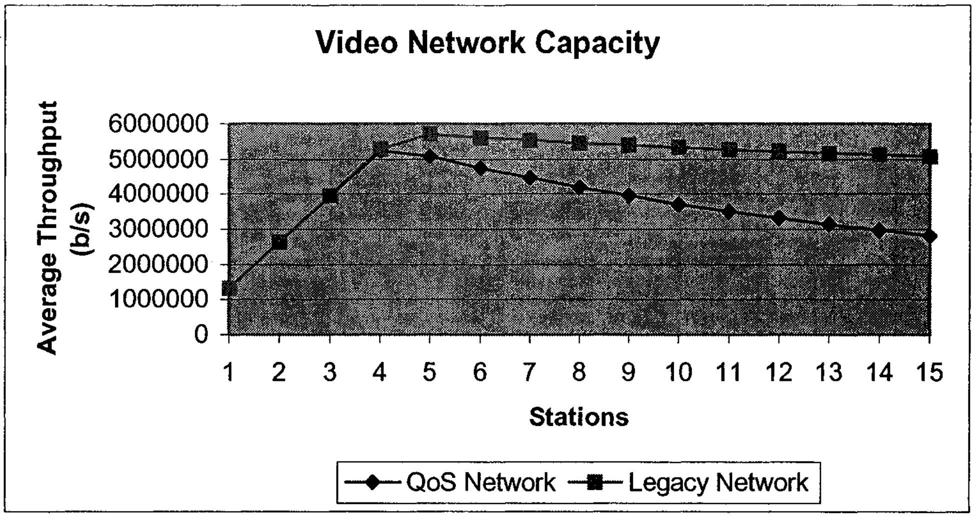


Figure 4. 6: Average Throughput for Video In QoS and Legacy Networks

From the obtained results, if a network consists only of video users, then it is more efficient to use the legacy IEEE 802.11 standard, since higher network capacity is achieved. This will be helpful in places that consist only of video users, such as the Internet Café, where all users are streaming music clips.

This finding is important, as it will prevent businesses having wireless networks with video traffic only from upgrading to the IEEE 802.11e. This will save huge amounts of money that would otherwise be necessary to upgrade the wireless network equipment. As discussed in this subsection, legacy networks perform better than QoS networks with pure video traffic only. Thus not upgrading to IEEE 802.11e and keeping with the legacy network will help to achieve better performance for the pure video wireless network. As with the analysis of the wireless networks with data only, the capacity of the pure video network was established, thus helping which businesses to plan their wireless networks.

4.5.3 Legacy Verses QoS Voice Networks

The aim of this scenario is to discover the IEEE 802.11e voice network capacity, i.e. what is the performance of the IEEE 802.11e network as the number of voice QSTA increases. A comparison was made between the QoS voice network and the legacy voice network. The metrics of this scenario is the global average network throughput. The value of the IEEE 802.11e parameters used in the voice QSTA are CW_{min}= 3 and CW_{max}= 7, these values specified in the IEEE 802.11e draft to be used with voice traffic. While the values for a legacy voice station (non-QSTA) are CW_{min}= 15 and CW_{max}= 1023 (these values are defined in the IEEE 802.11 standard to be used by all kinds of traffic). Figure 4. 7 shows the topology used with three wireless voice stations. An extra wireless station was added in the simulation runs, where each run began with one station up to fifteen. All voice stations are generating voice traffic only (refer to Section 4.1).

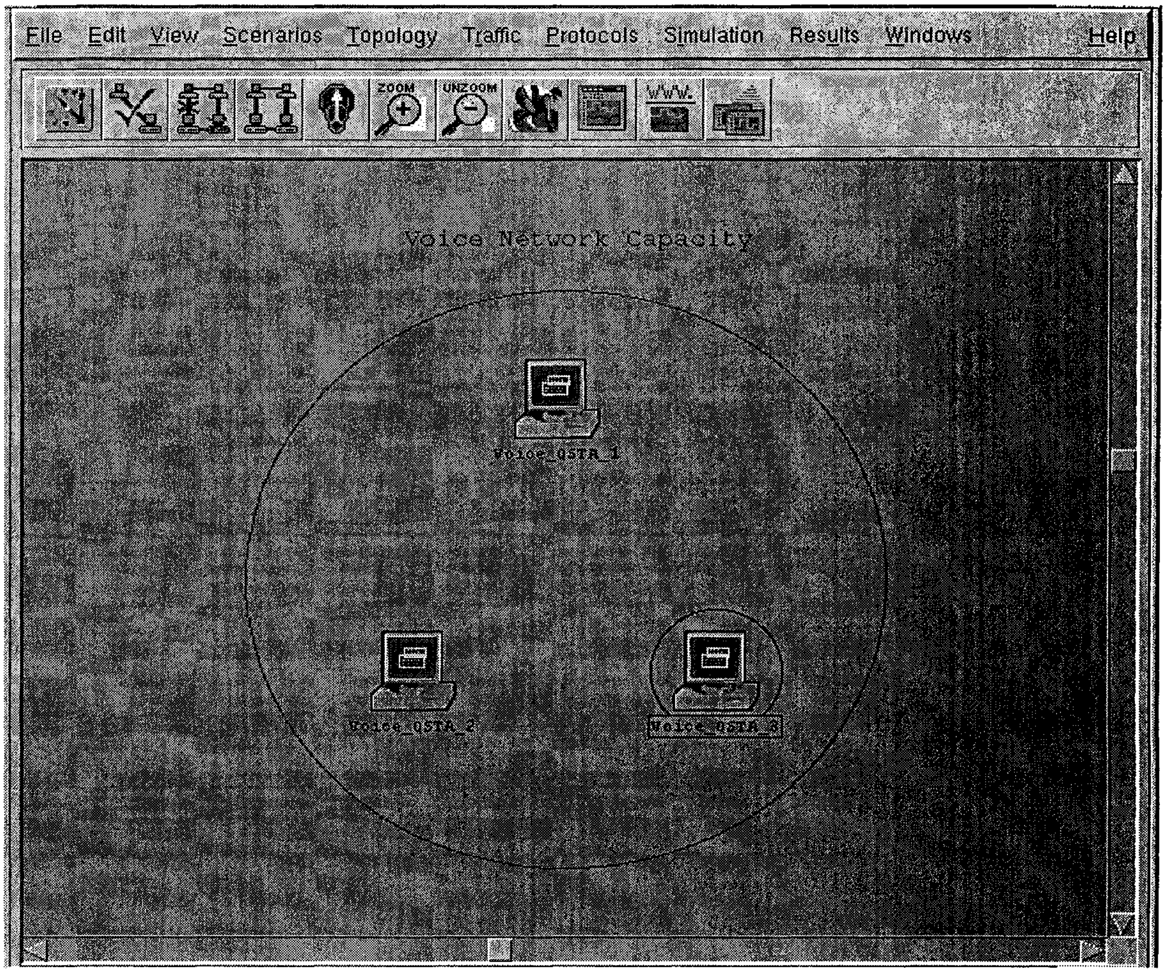


Figure 4. 7: Network Topology Used to Find The Voice Network Capacity

The graph in Figure 4. 8 shows the average throughput for legacy and the QoS network. The graph is linear for both networks up to ten voice stations, after which the QoS curve only starts to decrease. As discussed in Section 4.5.2, the decrease is due to the smaller interval CW_{min} to CW_{max} in voice QSTA compared to the legacy station, leading to higher collisions, hence decreasing the average throughput of the network.

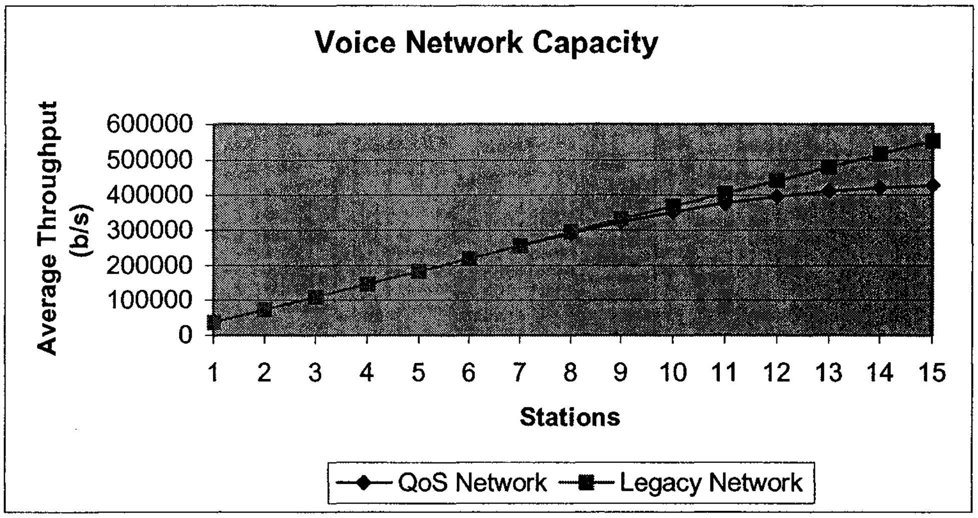


Figure 4. 8: Average Throughput for Voice In QoS and Legacy Networks

From the obtained results, it could be concluded that if a network consist only of voice users (with no data or video traffic) then it is more efficient to use the legacy IEEE 802.11 standard, since higher network capacity is achieved using the legacy network. This will be helpful in places that consist only of voice users, such as a conference room with all members connected through a VoIP.

Networks having traffic composed of only voice should not be upgraded to the IEEE 802.11e, as there will be reduction in the performance of the network. Businesses having voice traffic only are not in need to upgrade and will save the cost of buying new equipment. In actuality, the network will maintain better service than after an upgrade.

4.5.4 Prioritizing Voice and Video over Data Traffic

IEEE 802.11e improves WLAN QoS by prioritizing voice and video over data traffic (since voice and video traffic are time sensitive). Traffic prioritization was evaluated by simulating a QoS network, with each simulation run having an extra QSTA (carrying voice, video and data traffic) was added. Average throughput for each traffic category was recorded. Results obtained from these simulation runs are graphed in Figure 4. 9. The graph shows a plot of the number of stations verses the throughput ratio, i.e. average throughput divided by throughput for one station for that AC. The voice traffic stream demonstrates a linear behaviour till the fourth station, which means that the network is carrying all the offered voice traffic up to the fourth station. The throughput for video traffic stream starts decreasing after adding the third station. As for data traffic stream, the throughput starts to decrease after adding the second station (i.e. data traffic cannot be carried by the network after two stations).

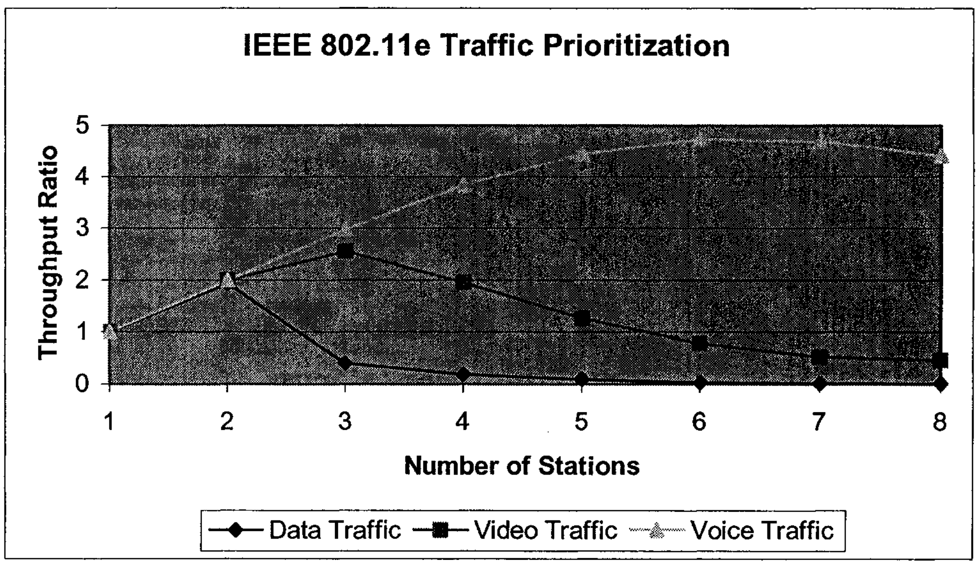


Figure 4. 9: Prioritization of Voice and Video Over Data Traffic

From the obtained results, it is clear that voice traffic has the highest priority over video and data (since four station's voice traffic is carried through the network while two and three only for data and video, respectively). Also from the obtained results, it is shown that the IEEE 802.11e gives the highest priority for voice traffic and the least priority for data traffic. Hence a prioritization technique is provided by IEEE 802.11e, giving better service for voice and video traffic over data traffic. This prioritization method will allow WLAN users to more efficiently use real-time applications, which will widen the application and the use of WLAN. Referring to Chapter 1, the cost to install a WLAN is cheaper than running wires to install a fixed wired LAN. With the prioritization and the improvement of the WLAN QoS, the WLAN will be deployed in many places, saving businesses the cost to install wired networks.

4.5.5 QoS Evaluation in Mixed Networks

Section 4.5.4 showed that QoS voice and video traffic have priority over data traffic. In this subsection a comparison will be made to rank the prioritization between legacy and QoS stations. To show the improvements achieved by the QSTA over the legacy station for voice and video traffic, the network in Figure 4. 10 was set up. The utilized network topology consisted of two voice, two video and two data stations, where there was one legacy and one QoS station for each traffic stream. The comparison of the obtained results is shown in Figure 4. 11.

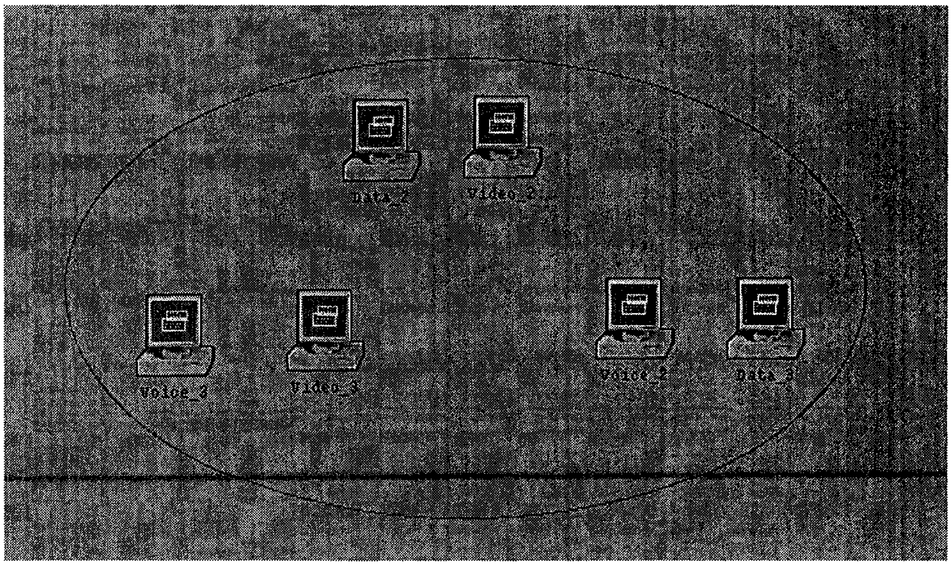
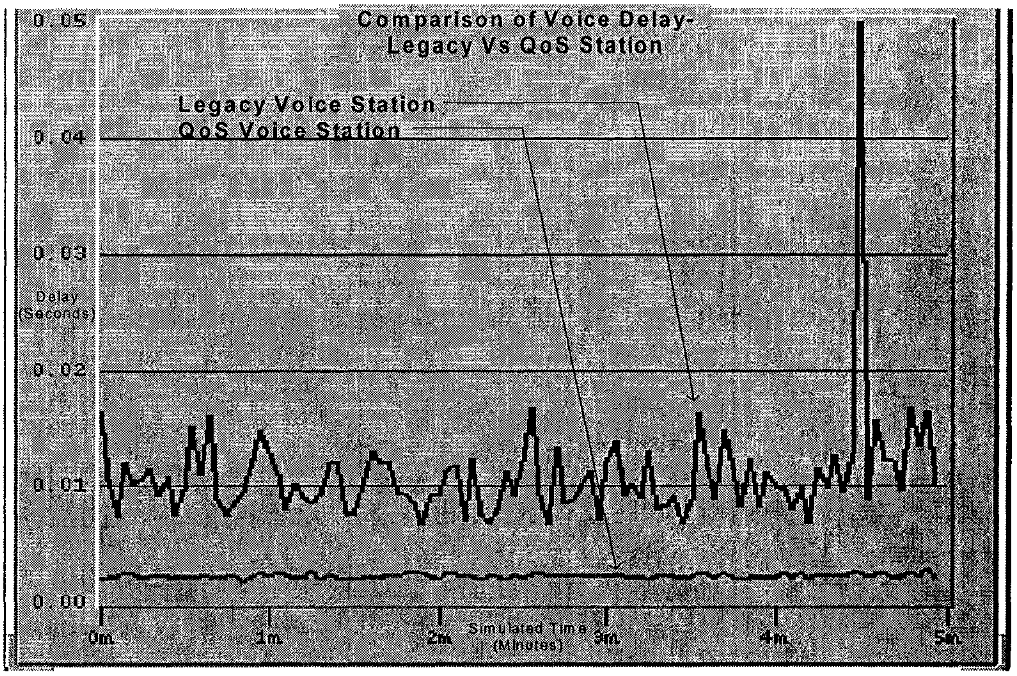
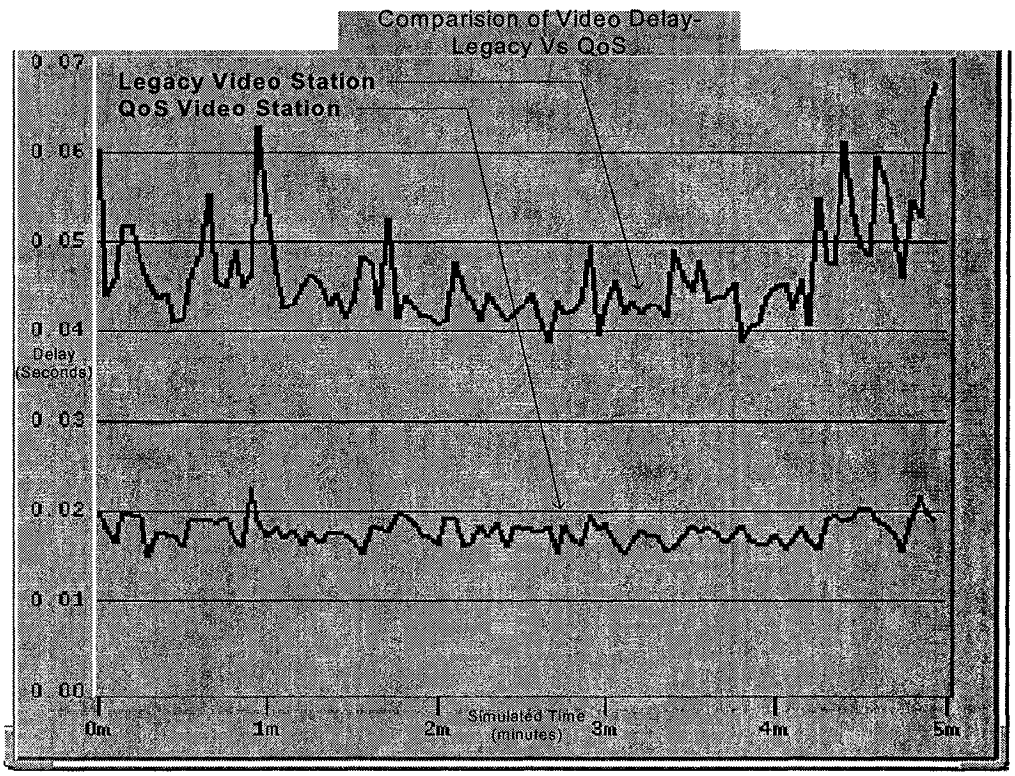


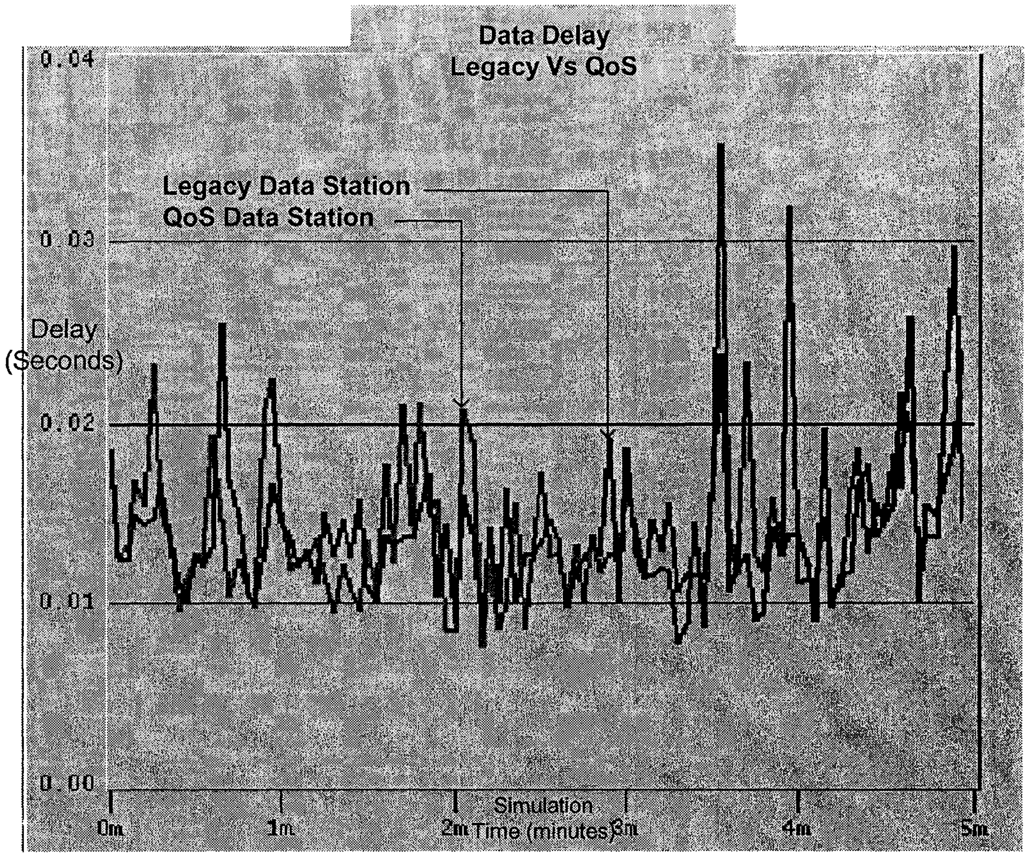
Figure 4. 10: Network Topology Used to Compare QSTA with Legacy Stations



(a): Comparison of Voice Delay for Legacy and QoS Stations



(b): Comparison of Video Delay for Legacy and QoS Stations



(c): Comparison of Data Delay for Legacy and QoS Stations

Figure 4. 11: Comparison of Voice, Video and Data Delay for Legacy Vs. QoS Stations

From the obtained results shown in Figure 4. 11 (a), it can be seen that QSTA voice traffic has priority over the legacy station voice traffic. Also, from Figure 4. 11 (b), it can be seen that QSTA video traffic has priority over the legacy station video traffic. Figure 4. 11 (c) showed that data traffic for legacy and QoS stations experience the same delay. These obtained results are significant to show the performance of the QoS stations when connected in a network with mixed traffic and legacy stations. It can also be concluded that QoS stations achieve better QoS results compared to legacy stations in a mixed network. The peak obtained in Figure 4.10 (a) could be because multiple stations transmitting at the same time and introducing lots of collisions, hence more delays.

4.5.6 Optimal Values for CWmin(AC) and CWmax(AC)

The IEEE 802.11e draft specifies default values for the parameters CW_{min}(AC) and CW_{max}(AC). The method defined in the draft to derive these default values is summarized in Table 4. 3 [13]. The values of the aCW_{min} and aCW_{max} referenced in the table are defined in the IEEE 802.11 standard as 15 and 1023 respectively.

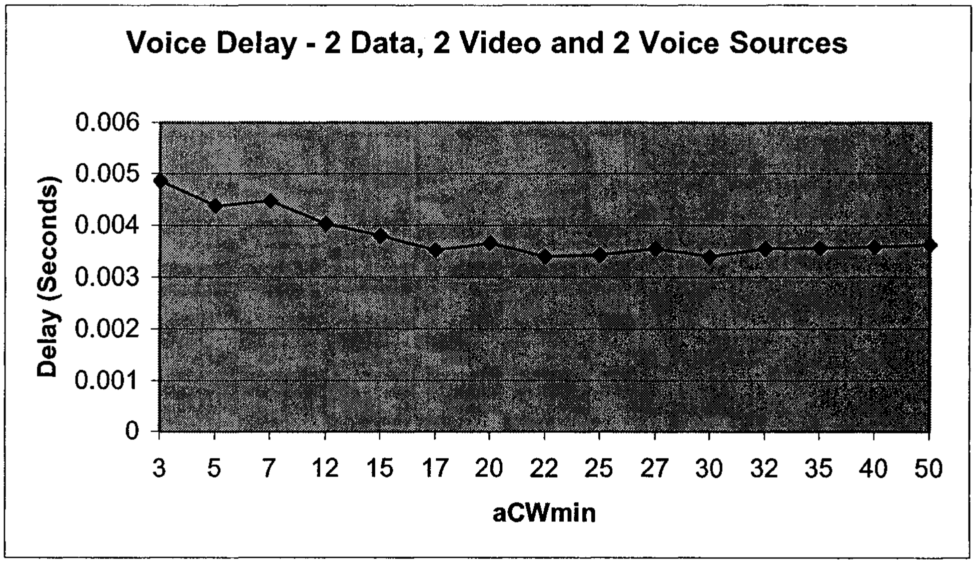
Table 4. 3
Default Formulas Specified for CWmin(AC) and CWmax(AC)

AC	CW_{min}(AC)	CW_{max}(AC)
Data	aCW_{min}	aCW_{max}
Video	$(aCW_{min} + 1) / 2 - 1$	aCW_{min}
Voice	$(aCW_{min} + 1) / 4 - 1$	$(aCW_{min} + 1) / 2 - 1$

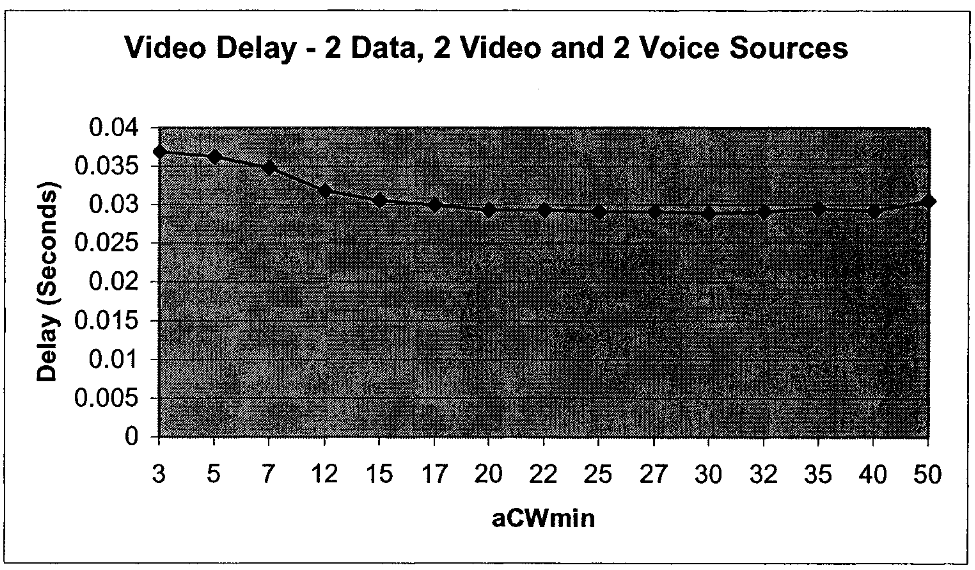
The simulated network was set up with two stations, each carrying voice, video and data traffic. For each simulation run, stations were configured according to the obtained values of CW_{min}(AC) and CW_{max}(AC) after plugging different value for aCW_{min} into the equations listed in Table 4. 3. The obtained throughput and delay for each traffic type was analyzed in order to find the optimal aCW_{min} and aCW_{max}.

As mentioned in Section 4.1, voice and video traffic are delay sensitive but tolerant to some frame losses, while data traffic is delay insensitive and intolerant to frame losses. Therefore, the optimal values of aCW_{min} and aCW_{max} should result in the minimum delay for voice and video traffic as well as high throughput for the data traffic. From Figure 4. 12, it can be seen that the minimum delay value for both voice and traffic is obtained when aCW_{min}=30. Figure 4. 13 shows that the data throughput is among the highest when aCW_{min}=30. For clarity the results are tabulated in Table 4. 4.

Comparing the value of the voice and video delay with aCWmin = 30 and with the default value of 15, it can be seen that the delay is improved by 11% for voice and 5% for video. This improvement will help all users of real-time applications to achieve better QoS. The improvement in data throughput will be 0.31%, which is a small but nonetheless still an enhancement.



(a) VOICE DELAY



(b) VIDEO DELAY

Figure 4. 12: VOICE AND VIDEO DELAY FOR VARYING aCW$_{MIN}$ FOR 2 STATIONS WITH DATA, VIDEO AND VOICE TRAFFIC

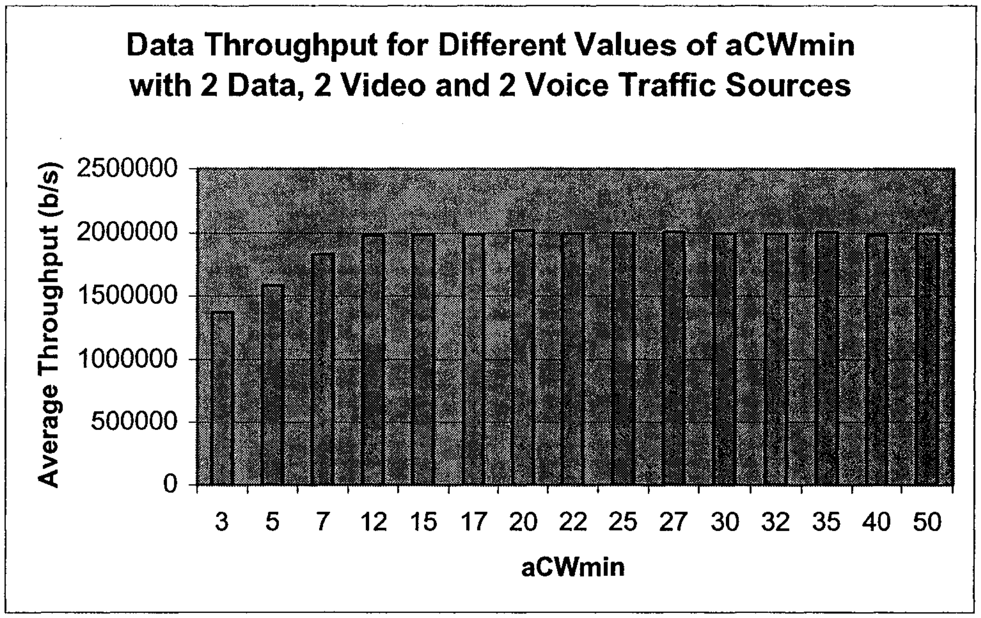
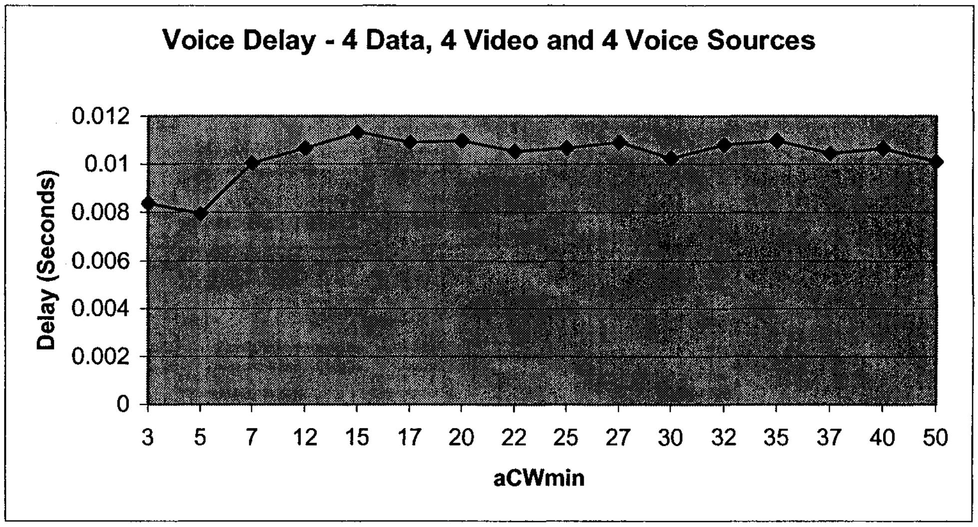


Figure 4. 13: Data Traffic Average throughput for varying aCWmin with 2 stations carrying voice, video and data traffic

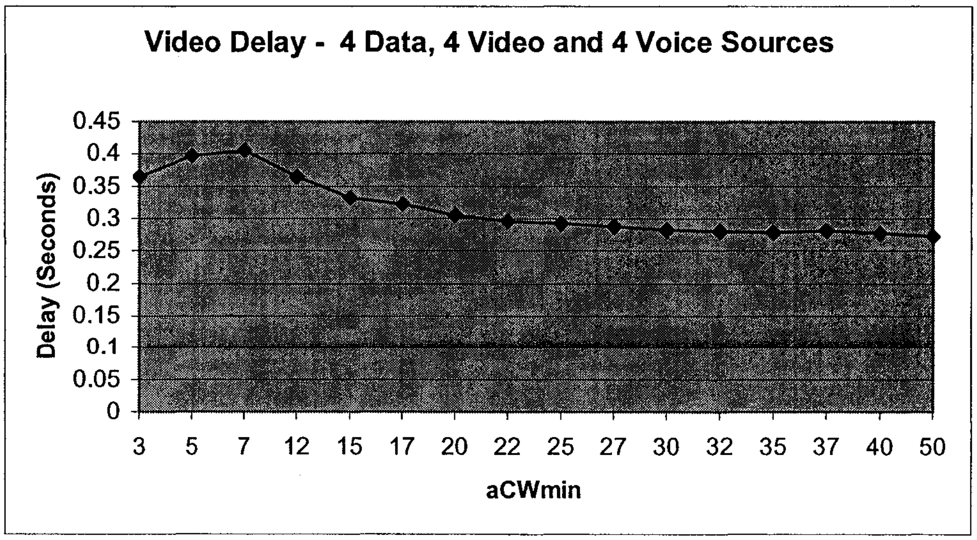
Table 4. 4
Values obtained for Voice and Video Delay and Data Throughput for 2 Stations Carrying Voice, Video and Data Traffic

aCW_{min}	Voice Delay (Sec.)	Video Delay (Sec.)	Data Throughput (bps)
3	0.004863391	0.036834891	1374880
5	0.004372786	0.036293131	1586680
7	0.004469412	0.034829301	1833080
12	0.004023476	0.031791132	1976480
15	0.003803619	0.030553891	1987880
17	0.003516270	0.029947158	1981920
20	0.003659069	0.029264565	2015160
22	0.003397515	0.029235498	1993520
25	0.003416528	0.029041989	1997800
27	0.003540595	0.029039784	2005360
30	0.003396061	0.028902031	1994120
32	0.003547784	0.029018655	1988000
35	0.003556809	0.029460063	2002680
40	0.003577463	0.029125594	1979200
50	0.003624057	0.030549271	1994240

To show that the value of aCWmin=30 is the optimal value, the above scenario was repeated with four stations each carrying voice, video and data (i.e. four voice, four video and four data traffic). It can be seen from the obtained results, tabulated in Table 4. 5 and plotted in Figure 4. 14 - Figure 4. 15, that the value for aCW_{min} is 30 is a reasonable value. The delay is improved by 10% for voice and 15% for video. This improvement will help all users of real-time applications to achieve better QoS. The improvement in data throughput will be 195%. This means that with the new optimal value for aCWmin the delay for voice and video are reduced and at the same time the data throughput is increased.



(a) VOICE DELAY



(b) VIDEO DELAY

Figure 4. 14: Voice and Video Delay for Varying aCWmin with 4 Stations with Data, Video and Voice Traffic

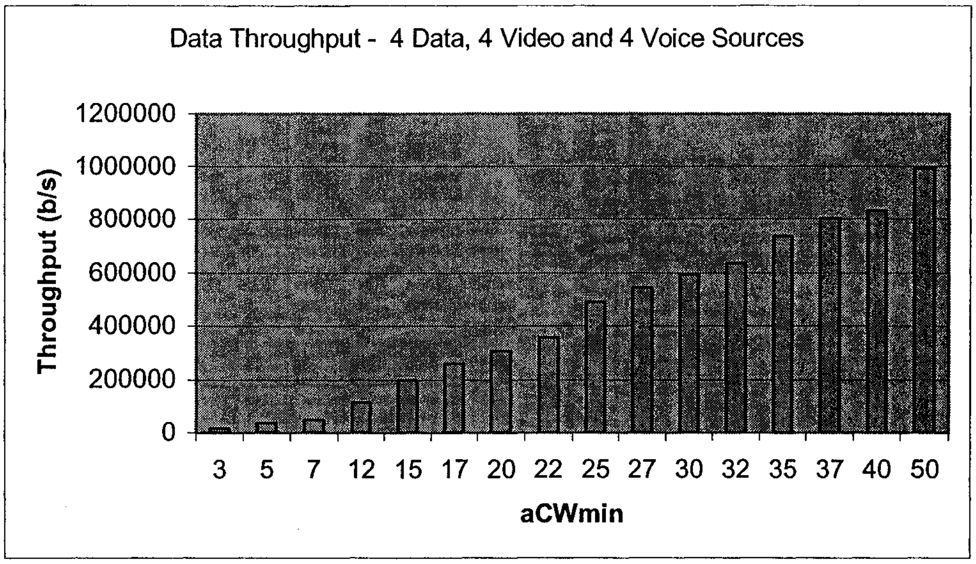
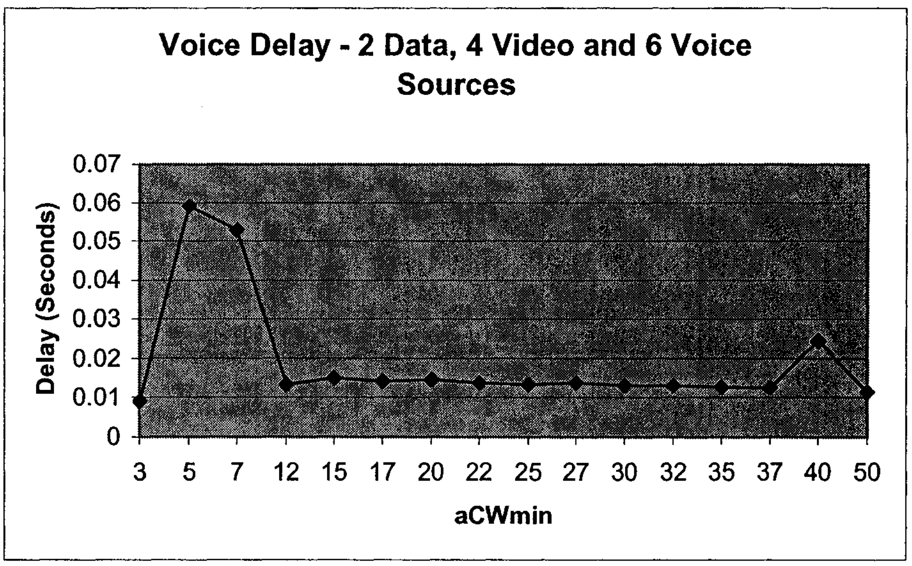


Figure 4. 15: Data Traffic Average throughput for varying aCWmin with 4 stations carrying voice, video and data traffic

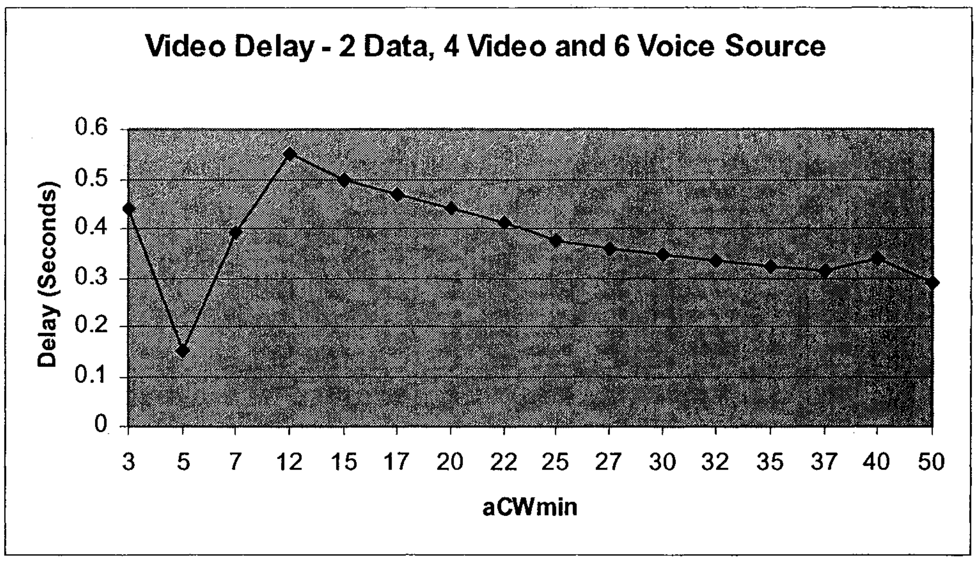
Table 4. 5
Values obtained for Voice and Video Delay and Data Throughput with 4 Stations Carrying Voice, Video and Data Traffic

aCW_{min}	Voice Delay (Sec.)	Video Delay (Sec.)	Data Throughput (bps)
3	0.008367550	0.364991490	14478
5	0.007909132	0.396392524	37643
7	0.010012976	0.405828833	49024
12	0.010676016	0.364718781	115960
15	0.011330991	0.332307667	200539
17	0.010899656	0.322043916	260593
20	0.010965746	0.305149329	305724
22	0.010522088	0.296434178	357576
25	0.010673801	0.292966469	489091
27	0.010891205	0.287836194	544983
30	0.010228446	0.283227816	592727
32	0.010810453	0.280635366	633805
35	0.010979240	0.279229829	737912
37	0.010441714	0.281790894	802694
40	0.010618218	0.277275339	833199
50	0.010105033	0.273076034	993737

Results from different network configurations were collected for various aCW_{min}. The reasonable value was aCW_{min}=30. For the configuration having two data, four video and six voice sources (results shown in Figure 4. 16 - Figure 4. 17 and Table 4. 6), the improvement achieved using the newly suggested value of aCW_{min}=30 (instead of the default value of 15) is voice and video traffic delay reductions of 13% and 31% respectively as well as a 339% increase in the data throughput! Results obtained for a different configuration having six data, six video and six voice sources comparing suggested value of aCW_{min}=30 with aCW_{min}=15 are voice and video traffic delay reductions of 20% and 19% respectively, and a 393% improvement in the data throughput. The results for this configuration are shown in Figure 4. 18 - Figure 4. 19 and Table 4. 7.



(a) VOICE DELAY



(b) VIDEO DELAY

Figure 4. 16: Voice and Video Delay for Varying aCWmin for 2 Data, 4 Video and 6 Voice Traffic Sources

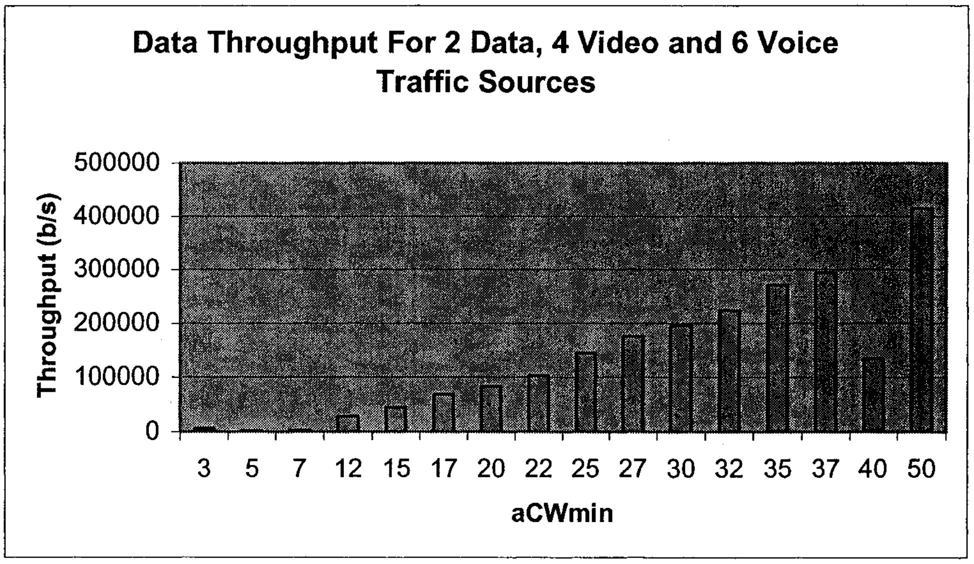
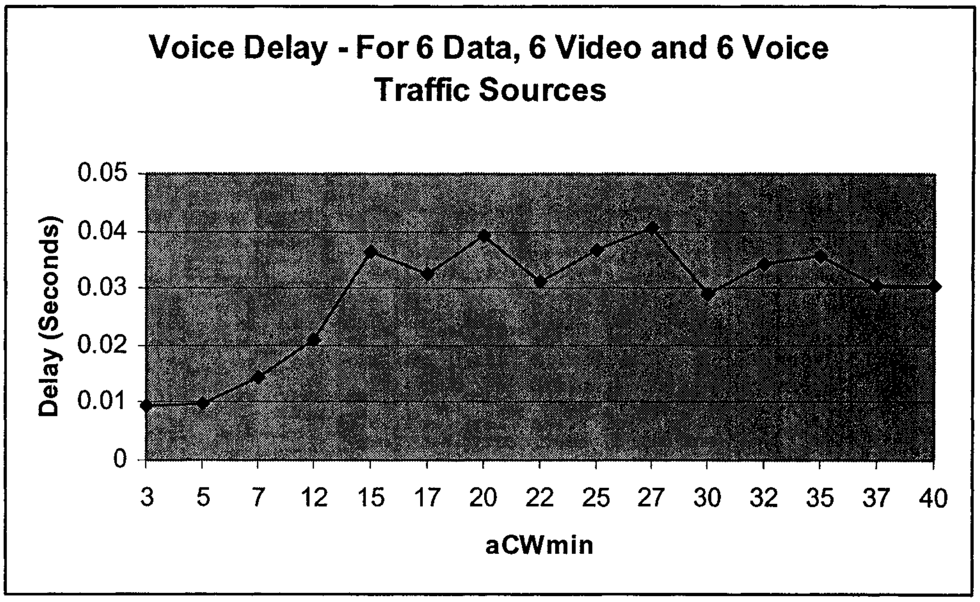


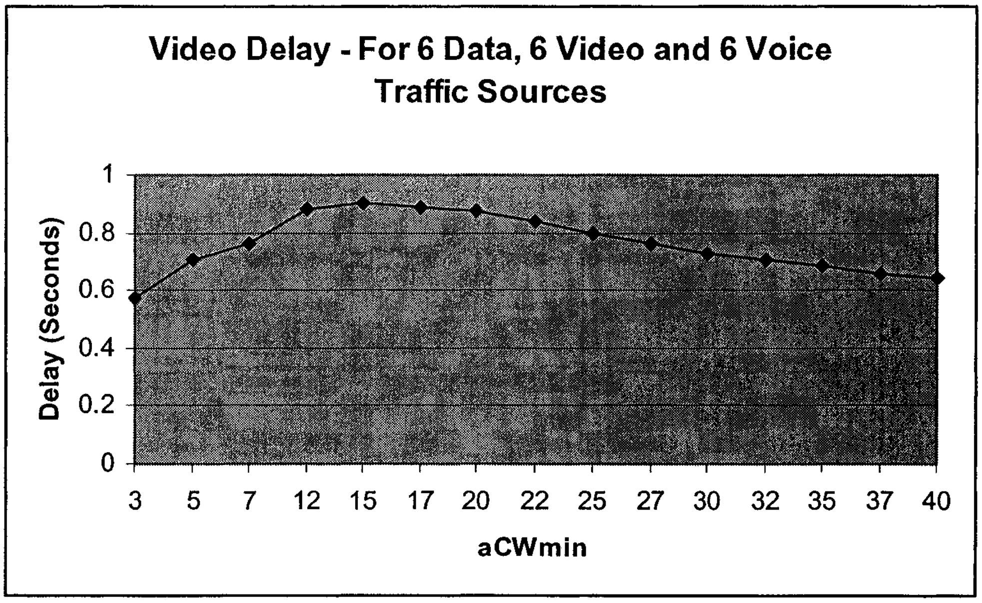
Figure 4. 17: Data Traffic Average throughput for varying aCWmin 2 Data, 4 Video and 6 Voice Traffic Sources

Table 4. 6
Values obtained for Voice and Video Delay and Data Throughput for 2 Data, 4 Video and 6 Voice Traffic Sources

aCW_{min}	Voice Delay (Sec.)	Video Delay (Sec.)	Data Throughput (bps)
3	0.009	0.44	5589
5	0.059	0.152	1212
7	0.053	0.392	3098
12	0.013401335	0.550753062	28013
15	0.01501	0.5	44512
17	0.01421	0.47	68350
20	0.01459	0.44	83300
22	0.013789974	0.411205886	103098
25	0.01346	0.375	144512
27	0.01389	0.361	176835
30	0.013084253	0.347142141	195286
32	0.01324	0.335	223569
35	0.01285	0.321	272323
37	0.012481623	0.313872304	293333
40	0.0246	0.338	134074
50	0.01159	0.289	414815



(a) VOICE DELAY



(b) VIDEO DELAY

Figure 4. 18: Voice and Video Delay for Varying aCWmin for 6 Data, 6 Video and 6 Voice Traffic Sources

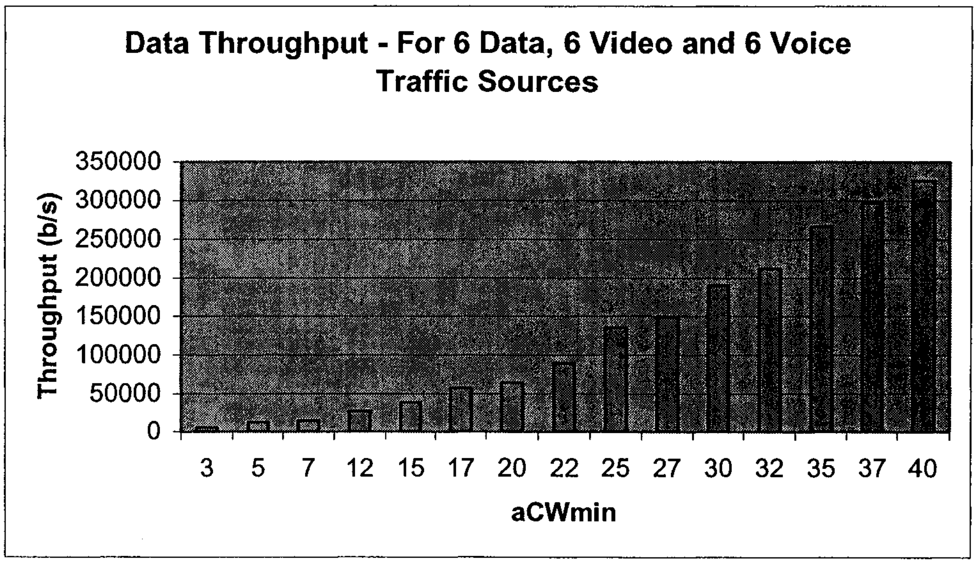


Figure 4. 19: Data Traffic Average throughput for varying aCWmin 6 Data, 6 Video and 6 Voice Traffic Sources

Table 4. 7
Values obtained for Voice and Video Delay and Data Throughput for 6 Data, 6 Video and 6 Voice Traffic Sources

aCW_{min}	Voice Delay (Sec.)	Video Delay (Sec.)	Data Throughput (bps)
3	0.009416842	0.570929603	5252
5	0.009658894	0.705387707	12323
7	0.014400310	0.765631563	15084
12	0.020931509	0.879285323	27071
15	0.036360386	0.901043674	38451
17	0.032604238	0.887957973	57643
20	0.039255544	0.872472040	64781
22	0.031252318	0.838762379	89495
25	0.036588032	0.794620313	135959
27	0.040534961	0.761240804	148888
30	0.029100123	0.725625061	189629
32	0.034204611	0.708470284	212121
35	0.035647394	0.683584253	266397
37	0.030337727	0.659922984	296364
40	0.030429705	0.642100992	326397

From the comparison of the obtained results for different configuration, using the suggested value of aCW_{min}=30 rather than the default value of aCW_{min}=15, a reduction in the voice and video delay was achieved varying from 5% to 31%, depending on the network load. These reductions in delay are important, as they will improve the voice and video QoS of the network. As mentioned earlier, the voice and video traffic are time sensitive which means that as the delay increases, the received video or voice traffic is of no use at the receiver station.

Reducing voice and video delay will improve the reliability and QoS of the wireless network in transferring voice and video traffic. Consequently, there will be an increase in the use of the WLAN real-time applications, hence increasing the deployment of WLAN in various businesses and the entertainment industry. For example, with a reliable QoS wireless network, businesses can increase the use of wireless VoIP and wireless videoconferences, so that a person waiting to board a train or an airplane will not miss his favourite hockey game but watch it live from the Internet through the WLAN connection provided in train stations and airports.

It is also important to note, that using the newly suggested value for aCW_{min}, a reduction in the delay of voice and video traffic is achieved as well as an increase in the data throughput. In some tested network configurations, an increase of 339% was achieved in the data throughput. This shows that the new value achieved less delays for voice and video traffic and at the same time not jeopardizing data traffic, but actually increasing the data throughput. This finding clearly shows that $aCW_{min}=30$ is the optimal value as it improved QoS for voice, video and data traffic. Ultimately the increase in the data throughput will permit users, connected to WLANs trafficking heavy voice and video traffic, to still able be to get their data traffic through.

4.6 Synopsis of Chapter 4

In this chapter, simulation was discussed as a tool for evaluating the QoS performance of the IEEE 802.11e. The analysis of the obtained results showed that the upcoming IEEE 802.11e provides prioritization for voice and video over data traffic. Interestingly, it was observed that the upcoming IEEE 802.11e standard does not enhance but rather degrades the QoS for networks with pure traffic (i.e. networks carrying one kind of traffic, either voice, video or data). This discovery led to the conclusion that it is not cost-effective or necessary to upgrade to the new IEEE 802.11e standard for networks carrying only one source of traffic. Through this assessment, an enhancement is also suggested and supported by simulation results to use a value of 30 for aCW_{min} instead of what the new draft suggests as a default value of 15. The parameter aCW_{min} affects the value of CW_{min} and CW_{max} for each AC, hence the QoS is notably improved with a value of 30. Significant reductions in traffic delay were additionally shown to be possible with this increased value of 30 so that users of wireless networks may benefit. This thesis will be summarized along with directions for future work in the coming final chapter.

Chapter 5

Conclusion and Future Directions

The IEEE 802.11e, as defined by the work group "e", is a future standard for improving the QoS of wireless networks. This draft of the future standard provides techniques for prioritizing voice and video over data traffic. Traffic prioritization is achieved by having a separate transmission queue for each traffic category. It is also attained by a separate channel access function as well as different values for CWmin and CWmax for each access category based on the traffic priority.

5.1 Summary of the Results Analysis

The evaluation of the IEEE 802.11e draft concluded that QoS performance is reduced using QoS stations in wireless networks with a single type of traffic (networks carrying voice traffic only). The legacy network showed better performance than QoS networks under single traffic type.

From the obtained results, it was concluded that mixed traffic network (those carrying voice, video and data traffic) priority is given to voice traffic from a QSTA over video and data. It was also concluded that priority is given to video traffic from a QSTA over data traffic. These results indicate that the IEEE 802.11e provides traffic prioritization.

During this work, a suggestion was made, backed by simulation results, to modify the default value of the parameter aCW_{min} in the IEEE 802.11e. This parameter is used to calculate CW_{min} and CW_{max} for the different ACs. It was suggested in chapter 4 to change the value of aCW_{min} from 15 to 30. With this change, a reduction in the delay of the voice and video traffic was achieved ranging from 5% to 31%, depending on the network load. This reduction in delay improves the QoS of the voice and video traffic, hence increasing the use of WLANs in real-time and time-sensitive applications. The newly suggested value reduces voice and video delay while simultaneously increases the data throughput. In some cases an increase of 339% in data throughput was achieved.

The enhancement suggestion should be considered by the Work Group "e" to improve the draft before becoming a solid standard that will be deployed in WLAN equipment. All such simulation outcomes infer that substantially increased QoS with potential large savings for businesses could be easily accomplished.

5.2 Contribution of this Thesis

The main contributions of this thesis to the technical community and users of wireless networks are:

- Evaluation of the QoS performance of the IEEE 802.11e.
- Indication that traffic differentiation in the IEEE 802.11 standard is lacking, and showing that this is remedied in the upcoming IEEE 802.11e.
- Determination of the QoS performance achieved by the draft in networks running one traffic type with all QSTAs. The QoS achieved in such networks with QSTAs was discovered to be worse than the performance achieved using the legacy stations.
- Fine-tuning of the draft by changing the value of the aCW_{min} parameter currently suggested in the draft. This change was supported by simulation results, with quantified improvements. The aCW_{min} parameter will affect the values of CW_{min} and CW_{max} for different ACs hence raising the overall QoS.

- The design and coding of the complete IEEE 802.11e OPNET model. This model can be used in future work for even further enhancements.

5.3 Future Work

Within the scope of this work, to fully assess the QoS performance of the upcoming IEEE 802.11e, OPNET was used to design and analyse the complete draft. A list of topics for future work, not addressed in this project for the sake of proper concentration on the assessment, is as follows. The model and results generated in this thesis would serve as foundation and jumpstart for such auxiliary work.

- Comparison of the IEEE 802.11e with other wireless network standards, such as the HIPERLAN, including the evaluation of the two different standards and analysing the QoS for each.
- Integration and performance evaluation of the IEEE 802.11e with the cellular network such as Universal Mobile Telecommunications Systems (UMTS), specifically how IEEE 802.11e could be integrated with UMTS to extend the application of wireless networks.
- Mapping DiffServ to MAC differentiation, i.e. how to achieve the optimal performance when mapping DiffServ to MAC differentiation provided in the IEEE 802.11e.
- Evaluating the performance of the IEEE 802.11e using different physical layers such as infra-red or DSSS (explained in Appendix A).

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Appendix A

IEEE 802.11 Physical Layer

The IEEE 802.11 standard [4] specifies three different physical layer implementations: Infra-Red (IR) baseband PHY and two radio frequency PHYs which are Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). A brief description on each implementation of the IEEE 802.11 physical layer is given in this appendix.

Infra-Red (IR)

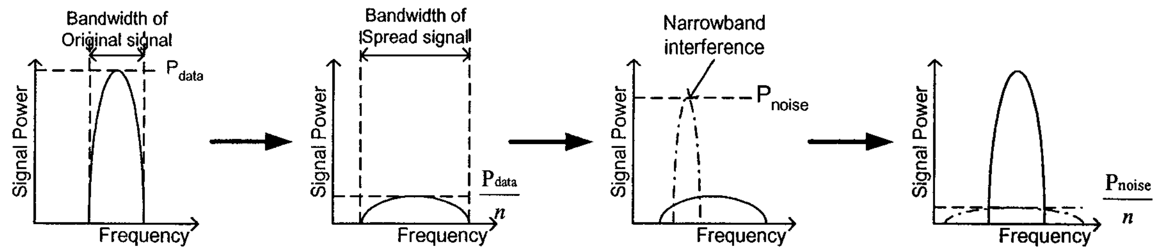
The IR specification utilizes part of the electromagnetic spectrum near visible light with a wavelength range from 850 to 950 nm for signalling. IR possesses essentially all the physical properties of visible light, immune to radio interference and operates in a bandwidth not regulated by the government. Infrared components are small and consume little power. In contrast to the radio systems that employ a common antenna for transmission and reception, IR systems uses two different components to transmit and receive optical signals [4].

Similar to visible light, IR operates at very high frequency, travels in straight lines, cannot penetrate opaque objects and physical obstructions (e.g. ceilings, walls) and is attenuated by passing through windows. IR can be reflected off walls and pass through open doorways. That is why IR PHY operates indoors not requiring direct transmissions. Which means that stations can receive line-of-site and reflected transmissions, making it possible for stations to retain the connection even with physical constraints such as moving objects in the area. Using IR is not efficient in an environment with reduced reflecting surfaces. Encoding of the basic access rate of 1 Mbps is performed using 16-pulse position modulation (PPM), where 4 data bits are mapped to 16 coded bits for transmission. The enhanced access rate (2 Mbps) is performed using 4-PPM modulation, where 2 data bits are mapped to 4 coded bits for transmission [3].

Direct Sequence Spread Spectrum

The IEEE 802.11 DSSS standard operates at either 1 or 2 Mbps in the 2.4 GHz frequency band. In DSSS, the signal energy (power) is spread through the use of pseudorandom sequence across a wider band of frequency. This results in the use of a wider bandwidth with a lower power density making the data signal much less susceptible to electrical noise. Thus DSSS systems offer highly reliable transmission with relatively small signal-to-noise ratios and low interference. This allows the share of the same frequency band by multiple DSSS signals.

Spreading of a signal is achieved by combining it with a higher data rate bit sequence (known as a chipping or pseudonoise code) that divides the data according to a spreading ratio. At the receiver, the chipping code is used to de-spread the RF input, thus enabling the original data to be recovered. Also at the receiver end the energy of noise and interference that might have been added during the transmission is spread and suppressed by the chipping code; this is explained in Figure A. 1 [20].



Where P_{data} is the data signal power
P_{noise} is the noise signal power
P_{data}/n The spread data signal

Figure A. 1: Rejection of Noise and Interference in the DSSS

The chipping code may vary in length from as small as 11 bits to an extremely long sequence. The IEEE 802.11 uses relatively simple 11-chip Barker code that spreads the data 11 times before transmission. The speed at which the chipping codes are transmitted is called the chipping rate. Figure A. 2 shows an example of how the binary data is spread using 11-chip chipping code [20].

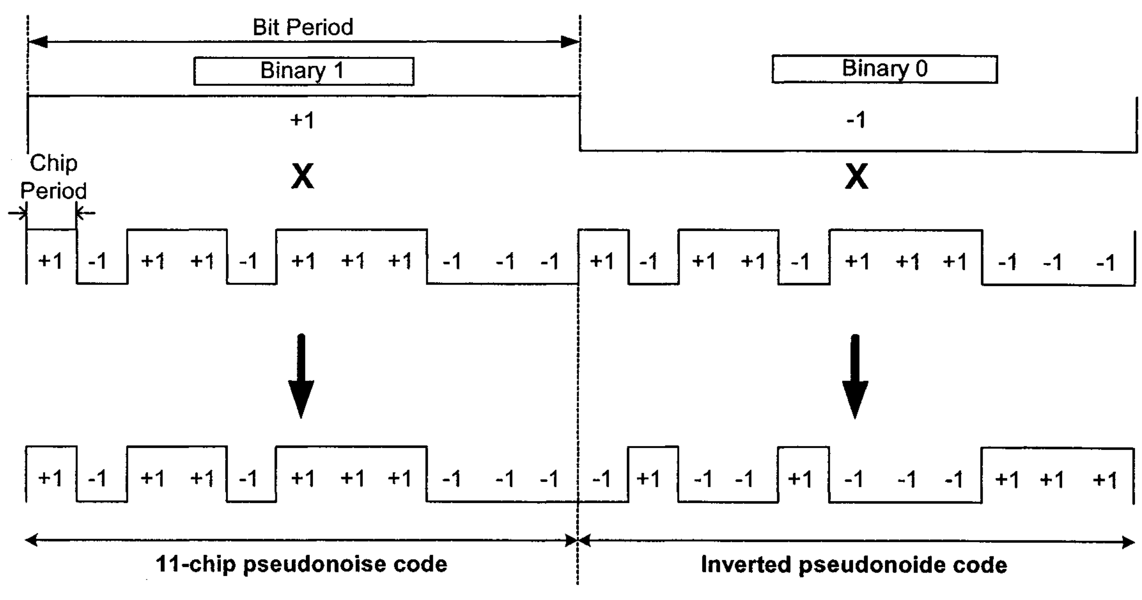


Figure A. 2: Spreading of binary data using 11-chip code

In addition to spreading the signal across a frequency band, spread spectrum systems modulate the signal. Modulation is the variation of a radio signal (carrier signal) to convey information. The 802.11 DSSS standard supports two different modulation techniques. At an operating rate of 1 Mbps, Binary Phase Shift Keying (BPSK) is employed; Quadrature Phase Shift Keying (QPSK) is used for an operating rate of 2 Mbps. BPSK detects 180-degree phase shift of the signal to represent a binary 1 or 0 while QPSK detects 90-degree phase shift thus doubling the data rate of BPSK. Figure A. 3 shows the DSSS processing model [20].

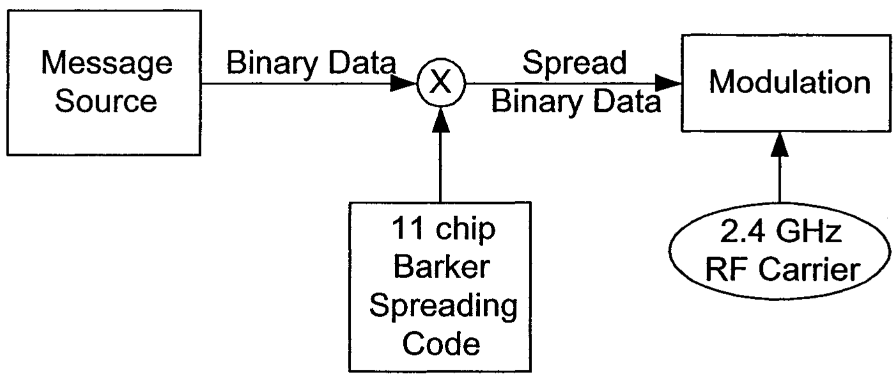


Figure A. 3: DSSS processing model

At the physical layer, DSSS transmits data using a predefined frame format that is shown in Figure A. 4 [4]. The DSSS frame is made of the following fields:

- 128 bits Preamble field which provides a mechanism for the receiving device to adjust to the incoming signal
- 16 bits Start of Frame Delimiter (SFD) field that provides symbol-level frame synchronization
- 8 bits signal field which indicates whether the data rate is 1 or 2 Mbps
- 8 bits service field which is reserved for future use
- 16 bits length field which indicate the number of bits in the data field thus the maximum size of the data field is 4095 bytes

- 16 bits Cyclic Redundancy Check field which is used for error checking of the signal, service and length fields

Bits

Preamble (128 Bits)	SFD (16)	Signal (8)	Service (8)	Length (16)	CRC (16)	DATA

Figure A. 4: DSSS PHY frame format

Frequency Hopping Spread spectrum

The third supported physical layer by the IEEE 802.11 is the Frequency Hopping Spread Spectrum (FHSS). In FHSS systems, the information signal is overlaid on a narrowband carrier that hops from one carrier frequency to another at a specific hopping rate in a predefined pattern known to both the transmitter and the receiver. Synchronization must be acquired and maintained between transmitter and receiver so that they are hopping on the same frequency channel at the same time. The IEEE 802.11 standard specifies seventy-nine non-overlapping frequency channels occurring at 1 MHz intervals within the 2.4 GHz band. This channel spreading enables up to twenty-six collocated networks to operate. The FHSS processing gain is the ratio of the total bandwidth occupied by the frequency channels over the signal bandwidth.

Frequency Shift Keying (FSK) is specified in the IEEE 802.11 as the modulation technique for the FHSS because of its low cost and ease of operation. Two variations of FSK are used which are referred to as two-level and four-level Gaussian-Shaped FSK (GFSK). At an operating rate of 1 Mbps two-level GFSK is used by which binary values are represented by deviating up or down from the base carrier frequency of the hopping channel. The upper deviation represents a 1, while the lower deviation represents a 0.

Transmission at 2 Mbps is obtained by using four-level GFSK, where pairs of modulated bits use one of four frequencies. IEEE 802.11 DSSS modulation techniques use the transmission power efficiently by utilizing multiple channels simultaneously. Where as the IEEE 802.11 FHSS modulation technique randomly utilizes multiple frequency channels. This randomness is one of the factors limiting the use of FHSS for higher-speed applications.

At the physical layer, FHSS transmits data using a predefined frame format that is shown in Figure A. 5 [4]. The field descriptions are the same as for the DSSS frame formats. By comparing the DSSS and FHSS preamble size, it can be noticed that FHSS requires less bits for synchronization.

Bits

Preamble (80 bits)	SFD (16)	Length (12)	Signaling (4)	CRC (16)	Variable Data

Figure A. 5: FHSS frame format

Synopsis of Appendix A

IEEE 802.11 specifies three different implementations of the physical layer, namely IR, DSSS and FHSS. IR reflects off walls and pass through open doorways. This is why IR is used indoors and should not be used in environments with reduced reflecting surfaces. The basic IR access rate is 1 Mbps and the enhanced access rate is 4 Mbps. DSSS operates in the 2.4 GHz frequency band at either 1 or 2 Mbps. BPSK and QPSK are the modulation techniques used in the rate of 1 Mbps and 2Mbps respectively. For FHSS, the IEEE 802.11 standard specifies a seventy-nine non-overlapping frequency channels occur at 1 MHz interval within the 2.4 GHz band.