Quality of Service in Wireless LAN Using OPNET MODELER

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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in
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Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"QoS in Wireless LAN Using OPNET MODELER"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in Computer Science Engineering submitted in Computer Science and Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. V.P. Singh and refers other researchers' works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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Abstract

Wireless local area networks (WLANs) are in a period of great expansion and there is a strong need for them to support multimedia applications. Wireless networks are becoming more and more popular in recent years, ranging from digital cellular telephony up to satellite broadcasting. With the increasing demand and penetration of wireless services, users of wireless networks now expect Quality of Service (QoS) and performance comparable to what is available from fixed networks.

Providing QoS requirements like good throughput and minimum access delay are challenging tasks with regard to 802.11 WLAN protocols and Medium Access Control (MAC) functions. This research is done to study, the presently implemented schemes (the Point Coordination Function (PCF) of IEEE 802.11, the Enhanced Distributed Coordination Function (EDCF) of the proposed IEEE 802.11e extension to IEEE 802.11), solves these issues and what can be done to improve them further.

The metrics used were Throughput, Data Drop, Retransmission and Medium Access Delay, to analyze the performance of various MAC protocols in providing QoS to users of WLAN. During the evaluation of EDCF, the performance of various access categories was the determining factor. Two scenarios, with same Physical and MAC parameters, one implementing the DCF and other EDCF, were created in the network simulation tool (OPNET MODELER) to obtain the results. The results showed that the performance of EDCF was better in providing QoS for real-time interactive services (like video conferencing) as compared to DCF, because of its ability to differentiate and prioritize various services. Whereas the DCF's overall performance was marginally better for all kinds of services taken together. In a network environment, where support for realtime interactive services is required, EDCF protocol should be used.

Abbreviations

AC	Access Category
AP	Access Point
AIFS	Arbitrary IFS
CW	Contention Window
DIFS	Distributed Coordination Function IFS
DCF	Distributed Coordination Function
EDCF	Enhanced Distributed Coordination Function
EIFS	Extended IFS
IFS	Inter Frame Space
MAC	Media Access Control
PCF	Point Coordination Function
PIFS	Point Coordination Function IFS
QoS	Quality of Service
RF	Radio Frequency
SIFS	Short Inter Frame Space
TXOP	Transmission Opportunities
WLAN	Wireless Local Area Network

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CHAPTER 1: Introduction

As the technology is improving so are the demands of end users and their applications increasing. A wide variety of new applications are being invented daily. These applications have different demands from the underlying network protocol suite. High bandwidth internet connectivity has become a basic requirement to the success of almost all of these areas.

Wireless Local Area Networks (WLANs) has become one of the most promising and successful technology in recent years. WLANs provide free wireless connectivity to end users, offering an easy and viable access to the network and its services.

Wireless networks are superior to wired networks with regard to aspects such as ease of installation and flexibility. They do, however, suffer from lower bandwidth, higher delays, higher bit-error rates, and higher costs than wired networks. With the advent of Wireless Local Area Networks (WLANs), bandwidth has increased and prices have decreased on Wireless networking solutions. These factors have made WLANs a very popular Wireless networking solution.

1. 1 Wireless Network

Wireless refers to the transmission of voice and data over radio waves. It allows its users to communicate with each other without requiring a physical connection to the network. Wireless devices include anything that uses a wireless network to either send or receive data [23].

Wireless communication has become the most promising way to connect people. Cellular systems have experienced exponential growth over the last decade and there are currently around two billion users worldwide. The first digital network based on packet radio, ALOHANET, was developed at the University of Hawaii in 1971. The Defense Advanced Research Projects Agency (DARPA) invested significant resources to develop it. In 1990, the first digital communication based cellular system was introduced. Since then, Radio technology advanced rapidly to enable transmissions over larger distances with better quality and less power. It enabled mobile communications and wireless networking [23].

1.2 Wireless Local Area Network (WLAN)

WLANs have revolutionized the way people are using their computers to communicate. As WLANs eliminate the need of wires for connecting end users, they provide a very easy, viable access to the network and its services. A wireless LAN or WLAN is a wireless local area network, which is the linking of two or more computers without using wires. WLAN utilizes spread-spectrum modulation technology based on radio waves to enable communication between devices in a limited area, also known as the basic service set. This gives users the mobility to move around within a broad coverage area and still be connected to the network. Wireless has become popular due to ease of installation and mobility.

To transport the data on a wireless network radio frequency, microwave and infrared are used as a transportation media [11].

1. **Radio frequency (RF)**

   RF refers to frequencies of radio waves. RF is part of electromagnetic spectrum that ranges from 3 Hz - 300 GHz. Radio wave is radiated by an antenna and produced by alternating currents fed to the antenna. RF was long been used for radio and TV broadcasting, wireless local loop, mobile communications, and radio.

2. **Microwave**

   Microwave is the upper part of RF spectrum having frequencies above 1 GHz. Because of the availability of larger bandwidth in microwave spectrum, microwave is used in many applications such as wireless Personal Area Network (Bluetooth), Wi-Fi, broadband wireless access (BWA) or wireless Metropolitan Area Network (WiMAX), wireless WAN (2G/3G cellular networks), satellite communications and radar. But it became very famous in houses because of its use in microwave oven.

3. **Infrared**

   Infrared light is part of electromagnetic spectrum that is shorter than radio waves but longer than visible light. Its frequency range is between 300 GHz and 400 THz that corresponds to wavelength from 1mm to 750 nm. Night vision equipment and TV remote control is using infrared from a long time. Infrared is also one of the physical media in the original wireless LAN standard, that's IEEE 802.11. Infra red use in communication and networking, defined by the IrDA (Infrared Data Association). Using IrDA specifications, infrared can be used in a wide range of applications, e.g. file transfer, synchronization, dial-up networking, and payment. However, IrDA is limited in range (up to about 1 meter). It also requires the communicating devices to be in LOS (Line of Sight) and within its 30-degree beam-cone [11].

1.2.1 Working of WLAN

Wireless networks perform functions similar to their wired Ethernet. Networks perform the following functions to enable the transfer of information from source to destination [17]:

1. The medium provides a bit pipe (a path for data to flow) for the transmission of data.
2. Medium access techniques facilitate the sharing of a common medium.
3. Synchronization and error control mechanisms ensure that each link transfers the data intact.
4. Routing mechanisms move the data from the originating source to the intended destination.
5. Connectivity software interfaces an appliance, such as a pen-based computer or bar code scanner, to application software hosted on a server.

1.2.2 Advantages of Wireless LAN

Flexibility: within radio coverage, nodes can communicate without further restriction. Radio waves can penetrate walls.

Planning: wireless ad hoc networks allow for communication without planning. Wired networks need wiring plans.

Robustness: wireless networks can survive disasters; if the wireless devices survive people can still communicate

1.2.3 Disadvantages of Wireless LAN

Connectivity: There are no wires to connect to the Wi-Fi network but then the area of the hotspot is very limited and if the node gets out of the area it will be disconnected. This is perhaps the greatest disadvantages you have to be within 100-150 ft of the base station (indoors) and about 100-300 meters (outdoors) to get connected.

QoS (Quality of Service): WLANs offer typically lower QoS. Lower bandwidth due to limitations in radio transmission and higher error rates due to interference.

Safety and security: using radio waves for data transmission might interfere with other high-tech equipment. The greatest challenge faced by Wi-Fi providers today is how to prevent outsiders from accessing the data.

1.3 Logical Architecture of WLAN

WLAN works in the lower two layers of OSI model. First one is the physical layer which takes care of transmission of bits through a communication channel by defining electrical, mechanical, and procedural specifications. Second one is the data link layer which is sub-divided into two layers: logical link layer (LLC) and Medium Access Control layer (MAC) [17]. Only MAC layer is considered as the part of wireless LAN Functions.

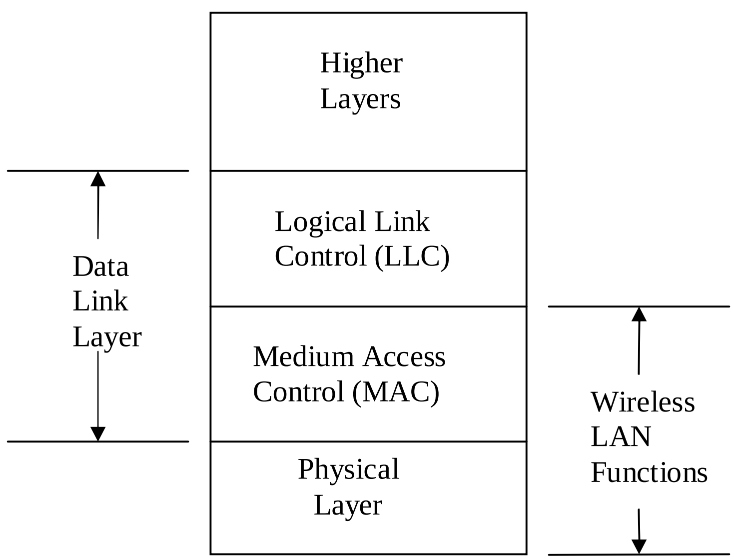


Figure 1.1 Logical Architecture of WLAN

1.3.1 Medium Access Control (MAC) Sub layer

The primary function of a MAC protocol is to define a set of rules and give the stations a fair access to the channel for successful communication. Many MAC protocols provide the standardized medium access and physical layer protocols for WLANs and it is the most widely employed standard in wireless networks.

Medium access control enables multiple wireless devices to share a common transmission medium via a carrier sense protocol similar to Ethernet. This protocol enables a group of wireless computers to share the same frequency and space. A wireless LAN Media Access Control protocol provides reliable delivery of data over somewhat error-prone wireless media.

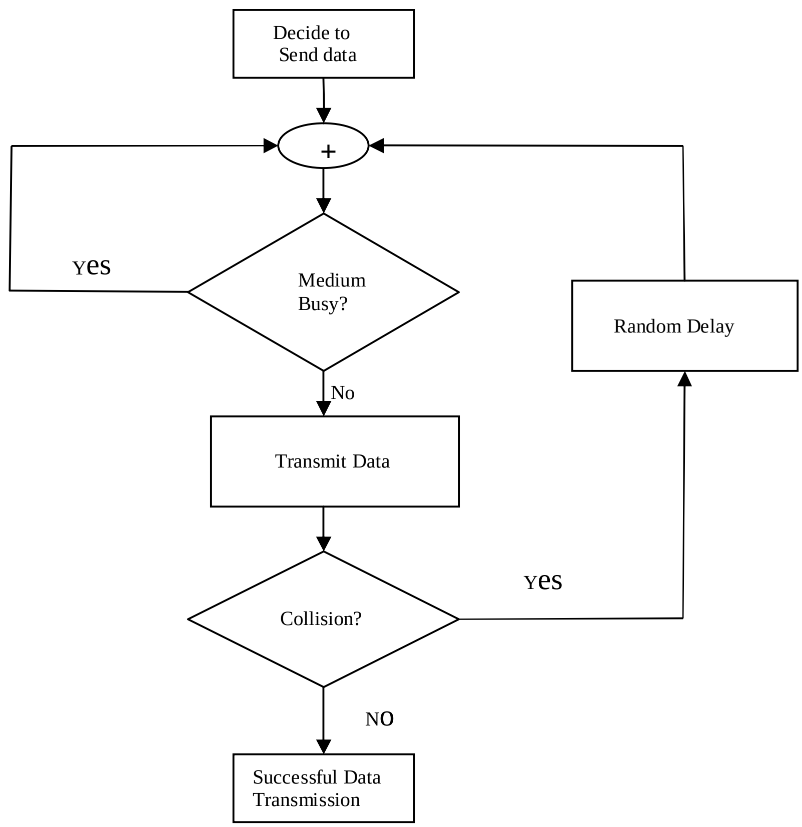


Figure 1.2 Working of CSMA protocol

1.3.2 Physical Layer

The Physical layer provides the transmission of bits through a communication channel by defining electrical, mechanical, and procedural specifications. Modulation, which is a Physical layer function, is a process in which the radio transceiver prepares the digital signal within the network interface card (NIC) for transmission over the airwaves. Spread spectrum “spreads” a signal’s power over a wider band of frequencies, sacrificing bandwidth in order to gain signal-to-noise performance [23]. This contradicts the desire to conserve frequency bandwidth, but the spreading process makes the data signal much less susceptible to electrical noise than conventional radio modulation techniques. Other transmission and electrical noise, typically narrow in bandwidth, will interfere with only a small portion of the spread spectrum signal, resulting in much less interference and fewer errors when the receiver demodulates the signal. Spread spectrum modulators commonly use one of two methods to spread the signal over a wider area: frequency hopping or direct sequence [23]. Main layer to be analyzed is MAC layer.

1.4 Physical Architecture of WLAN

There are two kinds of WLAN architectures:

- Ad-hoc (Infrastructureless) architecture
- Infrastructured architecture

Ad-hoc (Infrastructureless) Architecture

It is the simplest WLAN configuration. It is an independent (or peer-to-peer) WLAN and is also known as an Ad-hoc network. It is a group of computers each equipped with a wireless LAN client adapter. In this configuration, no access point is necessary and the devices in the LAN configure themselves at the same radio channel to enable peer-to-peer communication. Independent network can be set up whenever two or more wireless adapters are within range of each other.

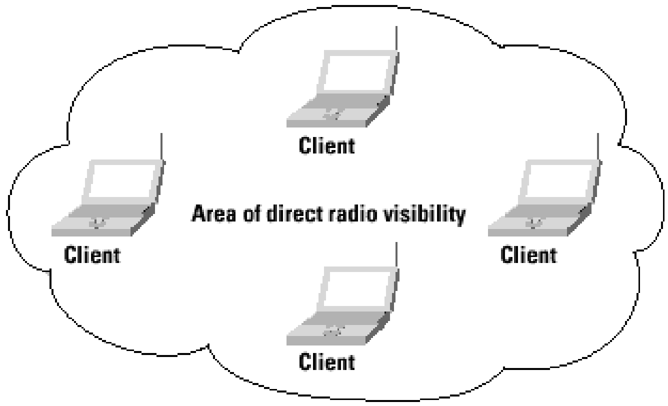


Figure 1.3 Infrastructureless Wireless Network

Infrastructured Architecture

Infrastructured WLAN consists of wireless stations and access points. Access Points are connected with a distribution system (such as Ethernet). Different access points create different cells having different locations and a confined communication radius. The mobile unit can move geographically while it is communicating. When it goes out of range of one base station, it connects with new base station and starts communicating through it. This is called “handoff” [23].

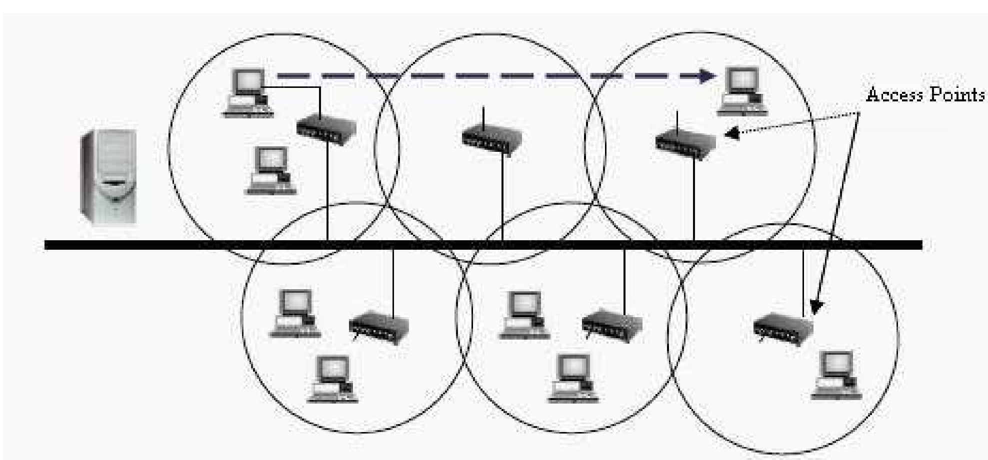


Figure 1.4 Infrastructured Wireless Networks

1.5 WLAN Components

The basic advantage WLAN has over LAN is the simplicity of its installation. Installing a wireless LAN system is easy and can eliminate the need of fitting cables through walls and ceilings. Basic components of a WLAN are access points (APs) and Network Interface Cards (NIC)/client adapters and these discussed as follows [3]:

Access Points

Access point (AP) is the wireless equivalent of a LAN hub. It is connected with the wired backbone through a standard Ethernet cable. It communicates with wireless devices with the use of antenna. An AP operates within a specific frequency spectrum. Most of the AP devices use the IEEE 802.11 standard, which enhances the interoperability. An AP also informs the wireless clients of its availability, authenticates and associates wireless clients to the wireless network.

Network Interface Cards (NICs)/Client Adapters

Wireless client adapter connect PC or Workstation to a wireless network either in adhoc (infrastructure less) peer-to-peer mode or in infrastructured mode with APs. It is available for two kinds of slots PCMCIA (Personal Computer Memory Card International Association) card and PCI (Peripheral Component Interconnect), it connects desktop and mobile computing devices wirelessly to the whole network. The NIC scans the available frequency spectrum for connectivity and associates it to an access point or another wireless client. It comes with a software driver that couples it to the PC operating system.

1.6 Quality of Service (QoS)

"QoS is defined as the ability of the network to provide a service at an assured service level"[9].

Quality of Service (QoS) is the ability to provide a level of assurance for data delivery over the network. For example, traffic of different classes or traffic with different requirements receives different levels of QoS assurance. Therefore, the term QoS support mechanism to refer to any mechanism that is equipped by any kind of QoS support. The term QoS guarantee will be referred to a mechanism that can provide guaranteed support. The objectives of QoS provision can be categorized into: a) prioritized QoS support and b) parameterized QoS support [6]. Prioritized QoS support aims at providing different level of QoS support for different classes of traffic, e.g., high priority traffic receives better throughput and delay than low priority class traffic. Prioritized QoS support is also known as differentiated QoS support. Parameterized QoS support aims at providing a specific level of QoS support, e.g., at least 64 Kbps and delay less than 30 ms, on average. Parameterized QoS support is also known as specific QoS support. Under prioritized QoS support, scheduling mechanisms classify packets into different priority classes. Under parameterized QoS support, scheduling mechanisms consider the requirement of a particular packet and provide the appropriate treatment.

The wireless communication was originally developed for army use, because of its ease of mobility, installation and flexibility; later on it was made available to civilian use also. With the increasing demand and penetration of wireless services, users of wireless network now expect quality of service and performance comparable to what is available from fixed networks. Some of factors that influence QoS of Wireless Network include:

1. **Throughput of Network**

   Represents the total number of bits (in bits/sec) forwarded from wireless LAN layers to higher layers in all WLAN nodes of the network.

2. **Retransmission Attempts**

   Total number of retransmission attempts by all WLAN MACs in the network until either packet is successfully transmitted or it is discarded as a result of reaching short or long retry limit.

3. **Data Dropped**

   Data dropped due to unavailability of access to medium.

4. **Medium Access Delay**

   It includes total of queuing and contention delays of the data.

1.7 Problem Definition

High raw data rates (up to 54Mbps as per standards and twice that in proprietary ways) at physical layer have become possible in wireless communication. A key component in the development of single channel wireless networks is the medium access control (MAC) protocol with which nodes share a common radio channel. A MAC protocol should provide an efficient use of the available bandwidth while satisfying the Quality of Service (QoS) requirements of both data and real-time applications. Real-time services such as streaming voice and video require a certain quality of service such as low packet loss and low delay to perform well. To provide QoS for such kind of application, service differentiation is must. Service differentiation means that different types of traffic have different requirements on the network. Various mechanisms have been developed to support quality of service but no effort has been made to implement the latest techniques in OPNET Modeler and compare them in order to know which one is the best under which type of traffic conditions. This research is an effort to know the pros and cons of various techniques and preparing recommendations for future development processes of QoS mechanisms in providing quality of service in WLANs.

The main objectives of the thesis are:

- The study of basic concepts and issues of Wireless/Cellular network that can improve the QoS of a cellular WLAN. Mainly focusing on Medium Access Control layer of Open Systems Interconnection (OSI) model.
- Study various existing Medium Access Control protocols of cellular WLAN.
- Implementation and comparison of efficient mechanisms that can improve the QoS of WLAN by using OPNET Modeler's wireless module.
- Study the results obtained, and recommend the best possible protocol that can provide high QoS under respective network traffic conditions.

1.8 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 surveys literature on QoS of WLAN from network perspective to user perspective. The categorization of MAC protocols is also discussed and then detailed working of various Medium Access Control (MAC) protocols is explained.

Chapter 3 explains the Work Flow Model of OPNET MODELER and various tools used to simulate a network.

Chapter 4 defines performance metrics used to compare the MAC protocols. In the end results are discussed.

Chapter 5 summarizes the work presented in the thesis followed by future scope of this work.

CHAPTER 2: Literature Survey

2.1 Introduction

This Chapter presents a comprehensive literature survey on different perspectives of QoS problem and its history. The detailed information about various functions affecting the QoS of WLAN in Layered Network model is also elaborated.

2.2 Quality of Service in WLANs

Wireless networking is an attractive networking solution due to its flexibility, mobility and ease of installation without damaging the furnishing of buildings (this factor play most important role in of situations where buildings are of higher heritage importance). In the earlier phases its development the wireless networks had low bandwidth, high bit-error rates and high prices which impeded their deployment [3]. When WLANs were introduced in full fledge, a new era of wireless networking began. Now, solutions based on WLANs provide a bandwidth close to that of wired networks at a competitive price. Because of this, wireless LANs are deployed at many places today. It is expected that with the increase in quality of service, the number of installation would increase and WLANs would cover even larger areas. Today, many places such as university campuses and corporate office space have coverage of wireless LANs, but the usage is often low because of unawareness among users about their presence and working, or not owning the required equipment to avail it. Users expect similar performance as when using wired network, so that they can use real-time application such as streaming audio and video over the WLAN. Scenarios such as these show a need for the ability to provide some service differentiation between users to facilitate for applications with higher demands on the quality of service they receive. Service differentiation means that different types of traffic have different requirements on the network. For example, an interactive voice application becomes unusable if voice data packets are delayed more than 100 ms in the network [22]. On the other hand, a mail application or web browser does not have the same requirements on low delays. Therefore, it is reasonable to try to provide better service to certain kinds of traffic.

Because the Wireless Channel is Time-varying, two types of Scheduling can be Consider in Wireless network: a) Non-Opportunistic Scheduling and b) Opportunistic Scheduling.

In Non-opportunistic Scheduling, such decisions do not consider the Time-varying characteristics of the wireless channel. The Network resources are considered constant and do not change with time.

By Opportunistic, the ability of scheduler to allow packet transmission based on favorable Channel conditions [10]. In Opportunistic Scheduling, such decisions depend on the conditions of the Wireless Channel since the characteristics of Channel Wireless change with time and each user may perceive the quality of the Channel differently. For Opportunistic Scheduling, two types of fairness constraints were suggested [10]: a) Temporal fairness and b) Utilitarian fairness.

In the Temporal fairness scheme, time is used as the criterion to maintain fairness among Mobile Stations (MSs).

In Utilitarian fairness scheme, the achieved performance values, e.g. throughput, are used as the criterion to maintain the fairness among MSs. Therefore, the advantage of utilitarian fairness is that it ensures a certain level of performance. However, a user with an extremely poor channel could have a detrimental impact on the overall system performance.

The IEEE 802.11 standard specifies two access mechanisms, the contention based Distributed Coordinator Function (DCF), and the centralized solution known as the Point Coordination Function (PCF) [4]. Presently, however, in most available products, only DCF is implemented. Even though PCF can be used to provide some service differentiation, it has been previously shown to perform poorly [9]. Thus, the DCF access mechanism can be considered to be the solely used access mechanism and one problem that WLANs do suffer from is the effect of the contention based medium access mechanism. Since the mechanism is contention based, all nodes that have some data to send have to contend for the medium when it becomes idle through an exponential backoff based scheme. This has the consequence that as the number of nodes in the network increases, the throughput of the network decreases. There are however other proposed access mechanisms. Vaidya et al [26]. try to emulate fair queuing in wireless LANs, through a scheme called Distributed Fair Scheduling (DFS). Sobrinho and Krishnakumar propose Blackburst [21], a scheme designed to provide collision-free medium access to real-time traffic. Both Vaidya et al and Sobrinho's schemes, however, unable to address the issue of starvation of low priority traffic at very high loads, therefore both schemes are not considered useful to discuss[7]. The upcoming IEEE 802.11e standard contains an updated access mechanism known as the Enhanced Distributed Coordination Function (EDCF) with support for multiple traffic classes.

2.3 Perspectives of QoS Problem

Quality of services problem has two major perspectives: Network and Application/user [15].

2.3.1 Network Perspective

From Network Perspective, QoS refers to the service quality or service level that the network offers to applications or users in terms of network QoS parameters, including: latency or delay of packets traveling across the network, reliability of packet transmission, and throughput.

2.3.2 Application/User Perspective

From Application/User Perspective QoS generally refers to the application quality as perceived by the user. That is, the presentation quality of the video, the responsiveness of interactive voice, and the sound quality of streaming audio. We group applications and users in the same category because of their common way they perceive quality [15].

2.4 Layered QoS

The layered QoS approaches (philosophies) separate QoS aspects on each layer. In layered QoS approach each layer’s functions are considered important and determining to improve the quality of service of network. The performance of Transport, Network and data link layer is the most crucial factor among the other layers of OSI model.

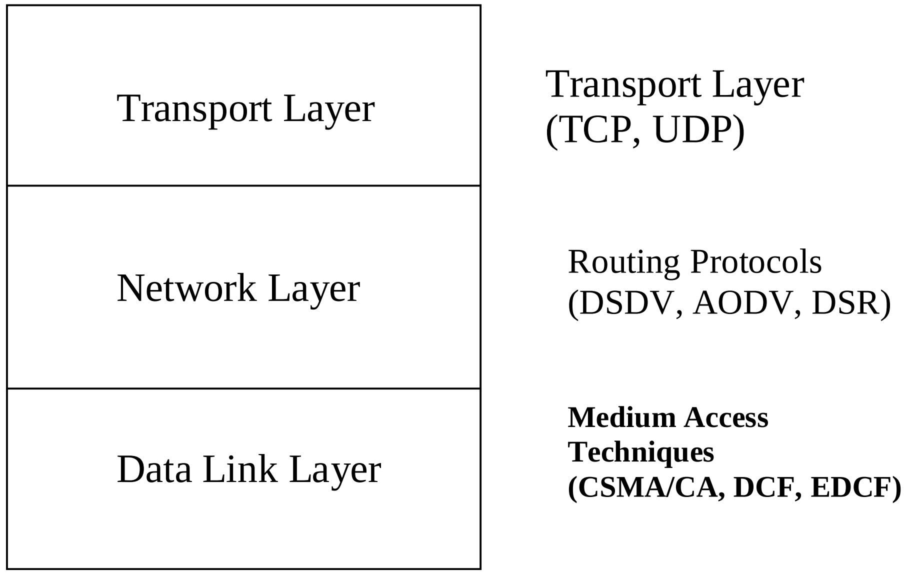


Figure 2.1 Layered QoS Approaches

As there has been lot of work done in Transport and Network layer, the performance of both layers in supporting QoS of WLAN is at acceptable level. But the data link layer is still lagging behind. IEEE 802.11, the official body that sets the standards for WLANs is continuously making efforts to improve it. In year 2005, IEEE passed a new standard 802.11e to provide QoS in WLANs [18]. A new protocol, EDCF in place of existing DCF has been purposed.

2.5 MAC Protocols Categorization

MAC protocols can be divided into two types [16]:

- Centralized
- Distributed

In centralized type of MAC protocols, a designated host (often referred to as base station or access point) co-ordinates access to the wireless medium. It's a contention free mechanism. PCF (point coordination function) is an example of this kind of protocol.

In distributed type of MAC protocols there is no arbitrator. Since the mechanism is contention based, all nodes that have some data to send, have to contend for the medium when it becomes idle through an exponential Backoff based scheme. For example, in CSMA (Carrier Sense and Multiple Access), a node wishing to transmit a packet does so only if does not hear another ongoing transmission. CSMA protocol is fully distributed since each node independently determines whether to transmit a packet or not. DCF and EDCF are the examples of Distributed type medium access protocols. Working of these protocols is discussed in the following section.

2.6 MAC Protocols

Distributed Coordination Function (DCF) is the currently used protocol that comes with an optional Point coordination Function (PCF) Protocol. Enhanced Distributed Coordination Function (EDCF) is the future protocol that promises to provide the QoS. The explanation of these protocols is as follows:

2.6.1 Distributed Coordination Function (DCF)

Distributed Coordination Function is the basic access mechanism used in IEEE 802.11.It uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm to mediate the access to the shared medium. Before discussing DCF, there is terminology used in technicalities that one needs to know; that are as follows:

Inter Frame Space (IFS) are the time a station waits when the medium is idle before attempting to access it. IEEE 802.11 defines several IFSs, and by using shorter IFS, the medium is accessed prior to stations using longer IFS. The standard defines four IFS in ascending order of time, in other words, descending order of priority.

Short Inter Frame Space (SIFS) is used to separate transmissions belonging to the single dialog (Fragment-ACK) and it is the minimum inter frame space. There is, at most, one single station to transmit at any given time, therefore giving it priority over all other stations. This value for 802.11 PHY is fixed to 28 ms, time enough for the transmitting station to be able to switch back to receive mode and be capable of decoding the incoming packet.

PIFS (Point Coordination Function IFS) is used by the Access Point (or Point Coordinator) to gain an access over the medium before any other station. The value is SIFS + Slot Time, i.e. 78 ms.

DIFS (Distributed Coordination Function IFS) used in case of sending data packets and management packets (such as beacons). Distributed IFS is the inter frame space used for a station willing to start a new transmission, which is calculated as PIFS plus one slot time, i.e. 128 ms .

EIFS (Extended IFS) is a longer IFS used by a station that has received a packet that could not understand. This is needed to prevent the station from colliding with a future packet, belonging to the current dialog.

Therefore, in an event of contention, acknowledgment will have higher priority than data and management packets. Because DCF was originally designed for data applications [24], its main weaknesses are the lack of QoS support (absolute throughput, relative throughput or delay support). The lack of any QoS support also means that DCF provides no fairness among different traffic classes or among different transmitting frame sizes.

Whenever a data frame is to be sent, the station senses the medium [20]. If it is free for at least a DCF interframe space (DIFS) period of time, the frame is transmitted. Otherwise, if the medium is busy, a backoff time B (measured in time slots which depends upon the characteristic of physical layer) is chosen randomly in the interval [0, CW], where CW is the contention window [26]. After the medium has been detected idle for at least a DIFS, the backoff timer is decremented by one for each time slot the medium remains idle. If the medium becomes busy during the backoff process, the backoff timer is paused, and is restarted when the medium has been sensed idle for a DIFS again. When the backoff timer reaches zero, the frame is transmitted. Upon detection of a collision (which is detected by the absence of an acknowledgment frame to the data frame), the contention window is redefined according to Equation (1).

$$\mathbf{CW[i] = 2^{(k+i)} - 1} \qquad - \quad (1)$$

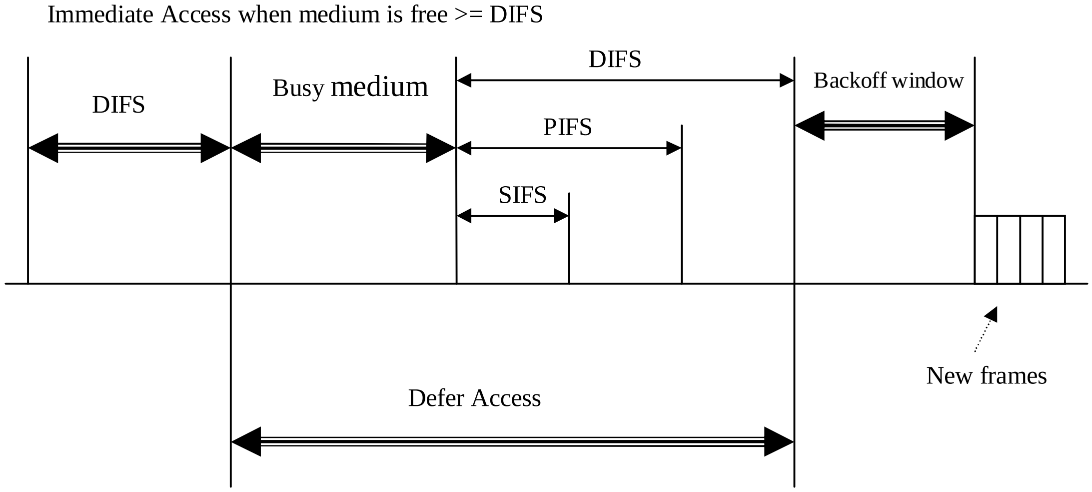


Figure 2.2 Interframe Space relationships

Where *i is* the number of attempts (including the current one) to transmit the frame that has been done, and *k* is a constant defining the minimum contention window, $CWmin = 2^k - 1$. A new backoff time is then chosen and the backoff procedure starts over. The backoff mechanism is also used after a successful transmission before sending the next frame. After a successful transmission, the contention window is reset to *CWmin*.

2.6.2 Point Coordinator Function

PCF is a polling-based access mechanism which requires the presence of a base station that acts as Point Coordinator (PC) [16]. If PCF is supported, both PCF and DCF coexist and, in this case, time is divided into superframes as shown in Figure 2.3 of Superframe of IEEE 802.11. Each superframe consists of a contention period where DCF is used and a contention free period (CFP) [26] where PCF is used. The CFP is started by a special frame (a *beacon*) sent by the base station. Since the beacon is sent using ordinary DCF access method, the base station has to contend for the medium, and therefore, the CFP may be shortened.

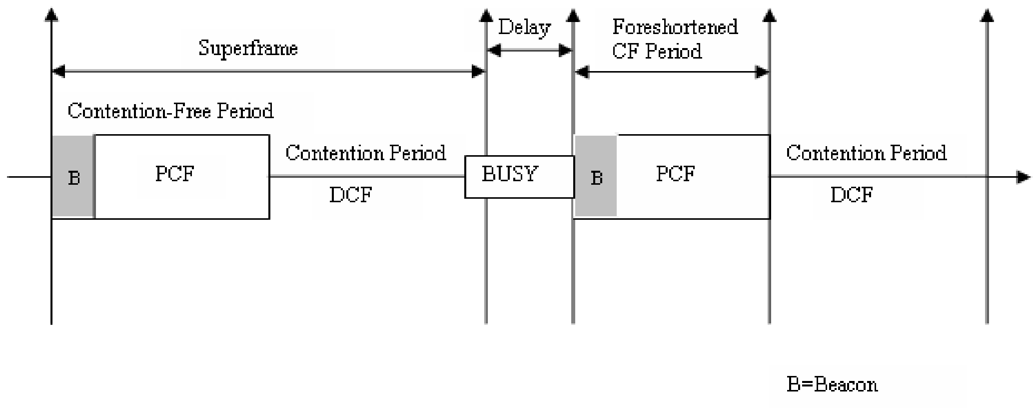


Figure 2.3 Superframe of IEEE 802.11

The PC keeps a list of mobile stations that have requested to be polled to send data. During the CFP, it sends poll frames to the stations when they are clear to access the medium. Upon reception of a poll frame, the station sends a data packet if it has any packet queued. To ensure that no DCF stations are able to interrupt this mode of operation, the IFS between PCF data frames is shorter than the usual DIFS. This space is called a PCF Interframe Space (PIFS) [1]. To prevent starvation of stations that are not allowed to send during the CFP, there must always be room for at least one maximum length frame to be sent during the contention period.

2.6.3 Enhanced Distributed Coordination Function

EDCF is designed to provide prioritized QoS by enhancing the contention-based DCF. It provides differentiated, distributed access to the wireless medium for QoS stations (QSTAs) using 8 different user priorities (UPs). Before entering the MAC layer, each data packet received from the higher layer is assigned a specific user priority value. The EDCF mechanism defines four different first-in first-out (FIFO) queues, called access categories (ACs) that provide support for the delivery of traffic with UPs at the QSTAs. Each data packet from the higher layer along with a specific user priority value should be mapped into a corresponding AC according to Table 2.1 [2].

Table 2.1 Details of Access Classes

Priority	Access Category(AC)	Designation
1	0	Background
2	0	Standard
0	1	Best Effort
3	1	Excellent Effort
4	2	Streaming Multimedia
5	2	Interactive Multimedia
6	3	Interactive Voice
7	3	Reserved

Note that the relative priority of 0 is placed between 2 and 3. This relative prioritization is rooted from IEEE 802.1d bridge specification. Different kinds of applications [1](e.g. best effort traffic, video traffic, and voice traffic) can be directed into different ACs. For each AC, an enhanced variant of the DCF, called an enhanced distributed channel access function (EDCAF), contends for TXOPs (Transmission Opportunities).

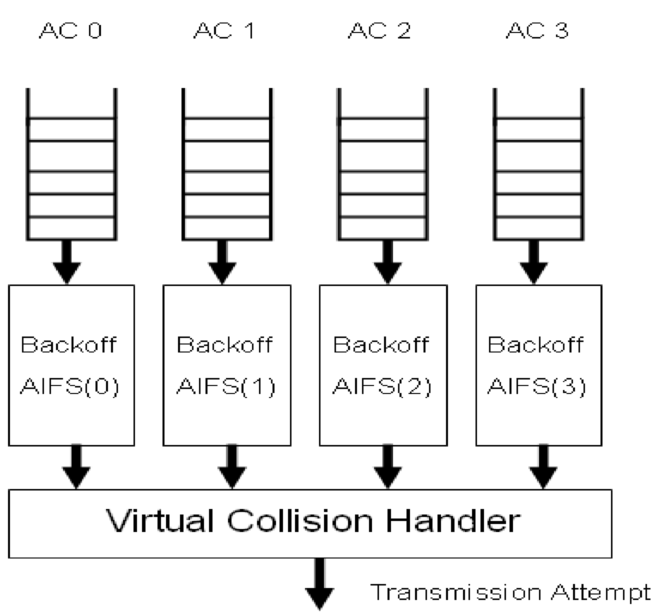


Figure 2.4 shows the implementation model with four transmission queues.

Where each AC behaves like a virtual station: it contends for access to the medium and independently starts its backoff after sensing the medium idle for at least AIFS period. In EDCF a new type of IFS is introduced, the arbitrary IFS (AIFS), in place of DIFS in DCF [16]. Each AIFS is an IFS interval with arbitrary length as follows:

$$AIFS[AC] = SIFS + AIFSN[AC] \times \text{slot time}$$

Where AIFSN[AC] is called the arbitration IFS number and determined by the AC and the physical settings, and the slot time is the duration of a time slot.

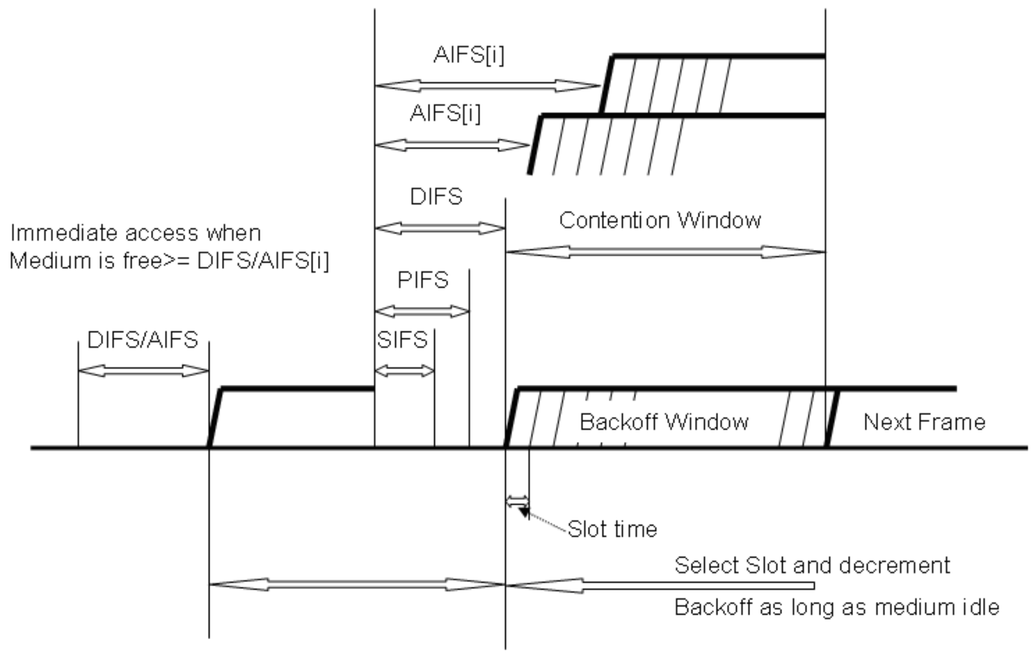


Figure 2.5 the timing relationship of EDCF

The AC with the smallest AIFS has the highest priority. The values of AIFS[AC], CWmin[AC], and CWmax[AC], which are referred to as the EDCF parameters, are announced by the AP(Access point) via beacon frames [1]. The purpose of using different contention parameters for different queues is to give a low-priority class a longer waiting time than a high-priority class, so the high-priority class is likely to access the medium earlier than the low-priority class. An internal collision occurs when more than one AC finishes the backoff at the same time. In such a case, a virtual collision handler in every QSTA allows only the highest-priority AC to transmit frames, and the others perform a backoff with increased CW values [7].

TXOP-Transmission opportunity is defined in IEEE 802.11e as the interval of time when a particular QSTA has the right to initiate transmissions. There are two modes of EDCF TXOP defined, the initiation of the EDCF TXOP and the multiple frame transmission within an EDCF TXOP [27]. An initiation of the TXOP occurs when the EDCF rules permit access to the medium. A multiple frame transmission within the TXOP occurs when an EDCF retains the right to access the medium following the completion of a frame exchange sequence, such as on receipt of an ACK frame. The TXOP limit duration values are advertised by the QAP (QoS station) in the EDCF Parameter Set Information Element in Beacon frames. During an EDCF TXOP, a STA is allowed to transmit multiple MAC protocol data units (MPDUs) from the same AC with a SIFS time gap between an ACK and the subsequent frame transmission. A TXOP limit value of 0 indicates that a single MPDU may be transmitted for each TXOP [7]. This is also referred to as contention free burst (CFB). The thesis investigates the situation where a station transmits one data frame per TXOP transmission round.

CHAPTER 3: Introduction to OPNET MODELER

3.1 Introduction

OPNET MODELER is used to design and study communication networks, devices, protocols and applications. It provides a graphical editor interface to build models for various network entities from physical layer modulator to application processes [12].

3.2 OPNET MODELER Tools

OPNET supports model specification with a number of tools, called editors. These editors handle the required modeling information in a manner that is similar to the structure of real network systems. Therefore, the model-specification editors are organized hierarchically. Model specifications performed in the Project Editor rely on elements specified in the Node Editor. The rest of the editors are used to define various data models, new links and nodes, etc. This organization is described below [1, 13, 7, 11]:

Project Editor

Project Editor is used to develop network models. Network models are made up of subnets and node models. This editor also includes basic simulation and analysis capabilities. The Project Editor is the main staging area for creating a network simulation. From this editor, you can build a network model using models from the standard library, choose statistics about the network, run a simulation and view the results. It is also possible to create node and process models, build packet formats, and create filters and parameters, using specialized editors that you can access from the Project Editor. In Figure 3.1 an example of the project editor view of a Wireless Network is shown.

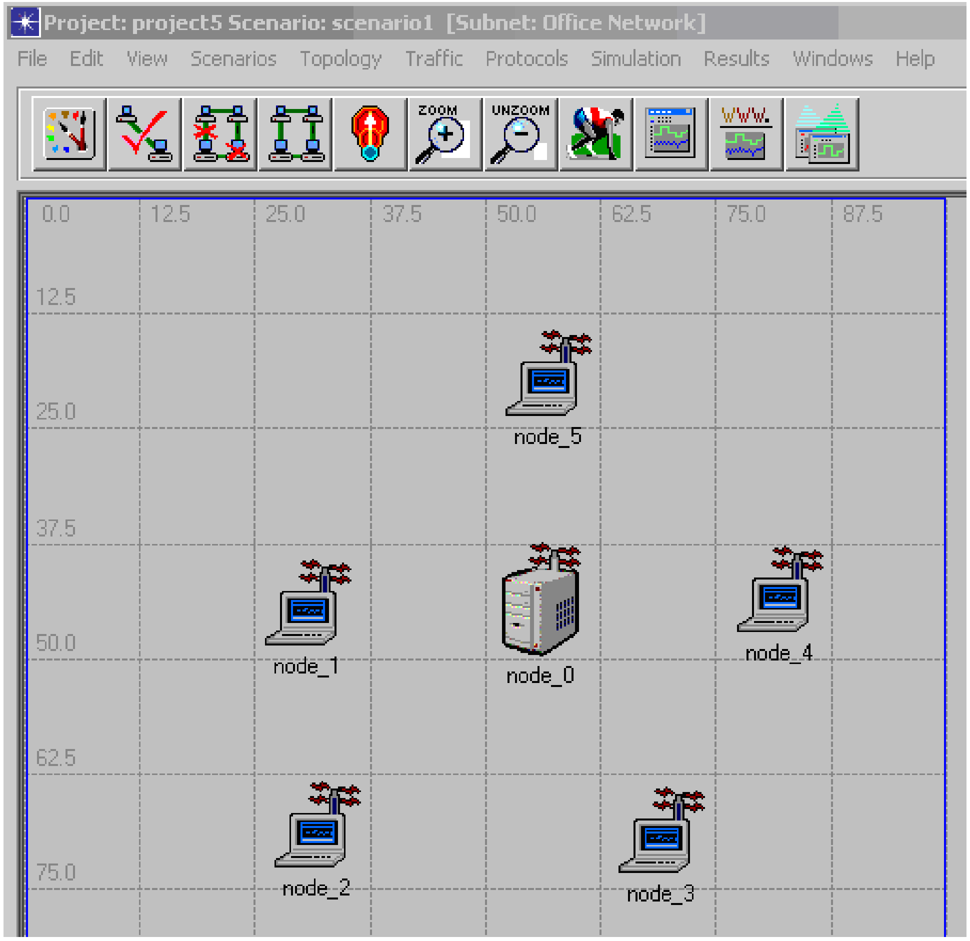


Figure 3.1 Project Editor - view of a Wireless Network

Node Editor

Node Editor is used to develop node models. Node models are objects in a network model. They are made up of modules with process models. The Node Editor lets you define the behavior of each network object. Behavior is defined using different modules, each of which models some internal aspect of node behavior such as data creation, data storage, etc. A network object is typically made up of multiple modules that define its behavior. In the Figure 3.2, there are some parts of a router's internal structure, such as a TCP module, an UDP module and an IP module.

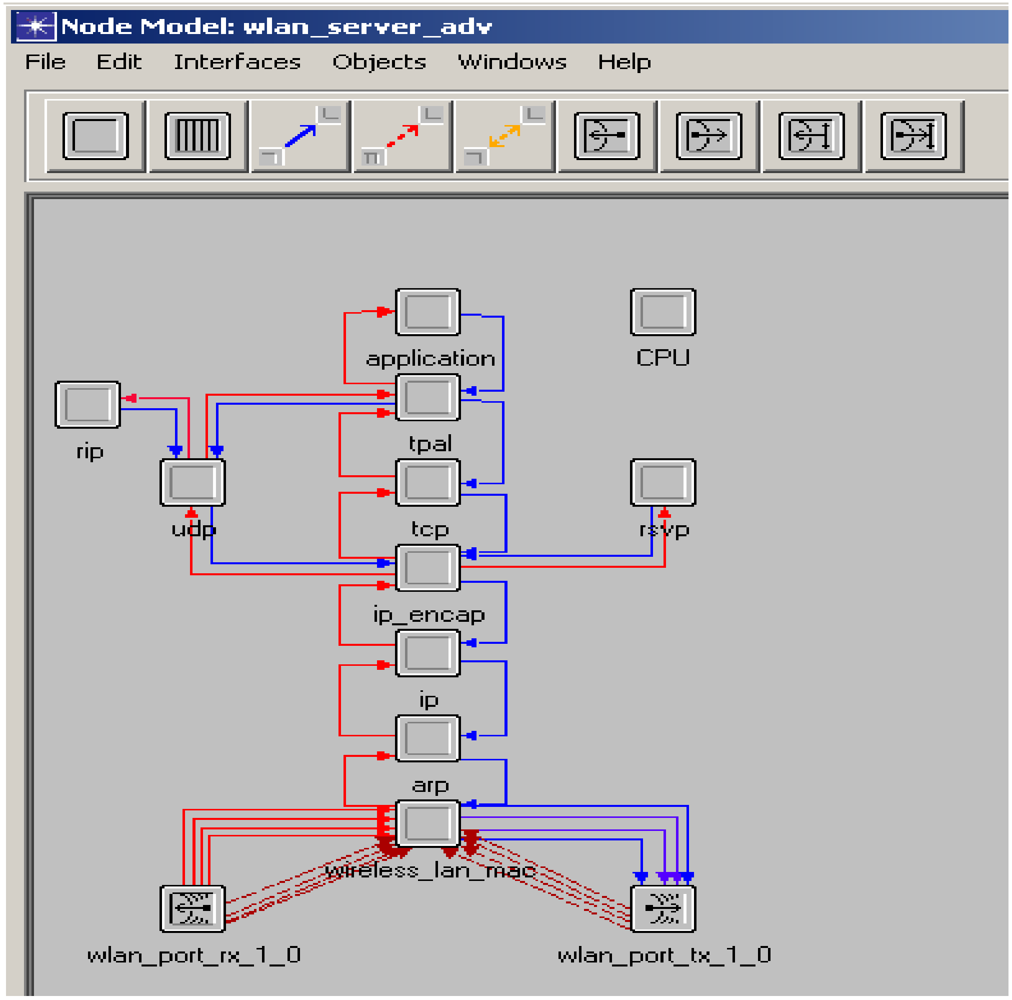


Figure 3.2 example of Node Editor

Process Editor

Process Editor is used to develop process models. Process models control module behavior and may reference parameter models. This editor lets you create process models, which control the underlying functionality of the node models created in the Node Editor [8]. Process models are represented by finite state machines (FSMs), and are created with icons that represent states and lines that represent transitions between states. Operations performed in each state or for a transition are described in embedded C or C++ code blocks.

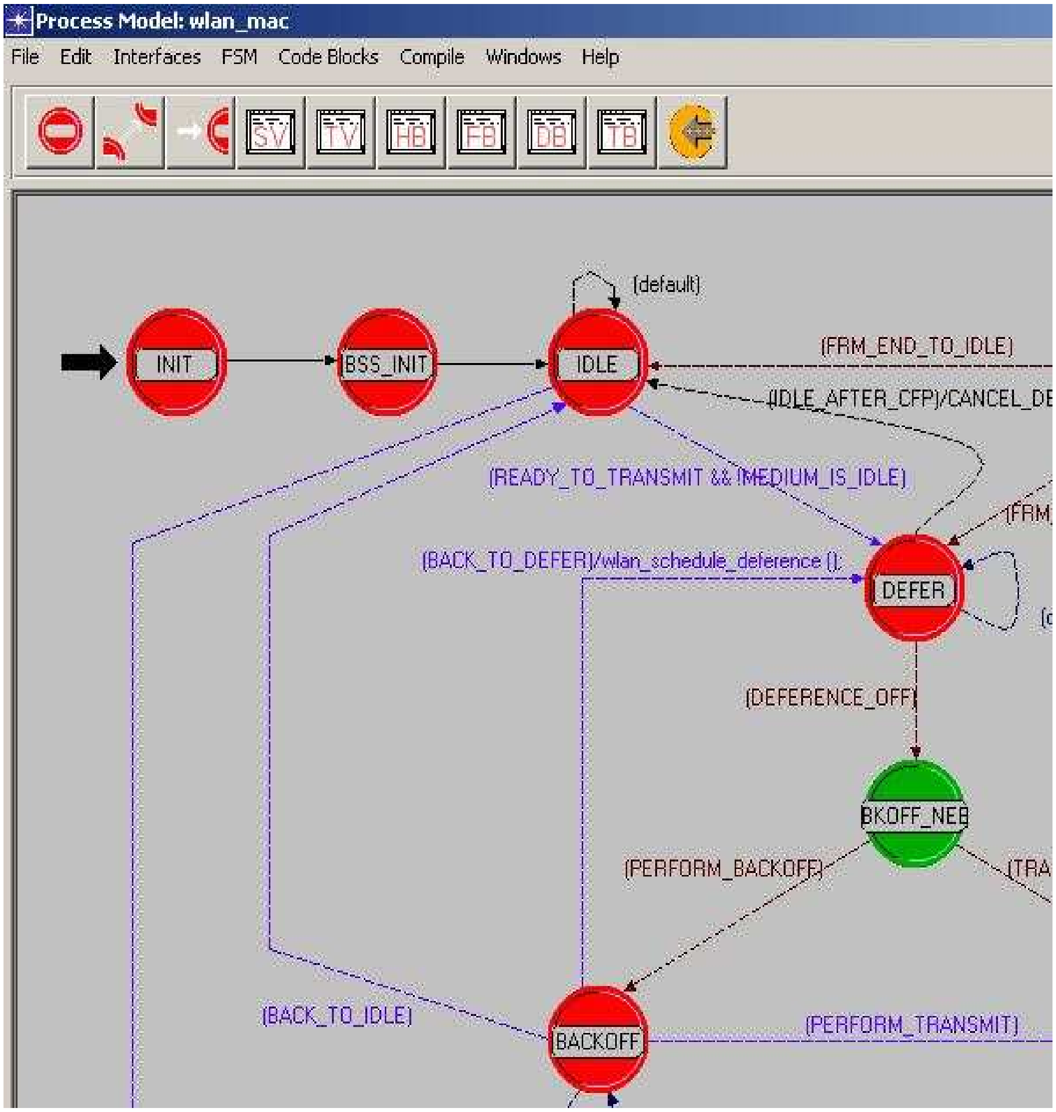


Figure 3.3 example of process model

External System Editor

External System Editor is used to develop external system definitions. External system definitions are necessary for simulation.

Link Model Editor

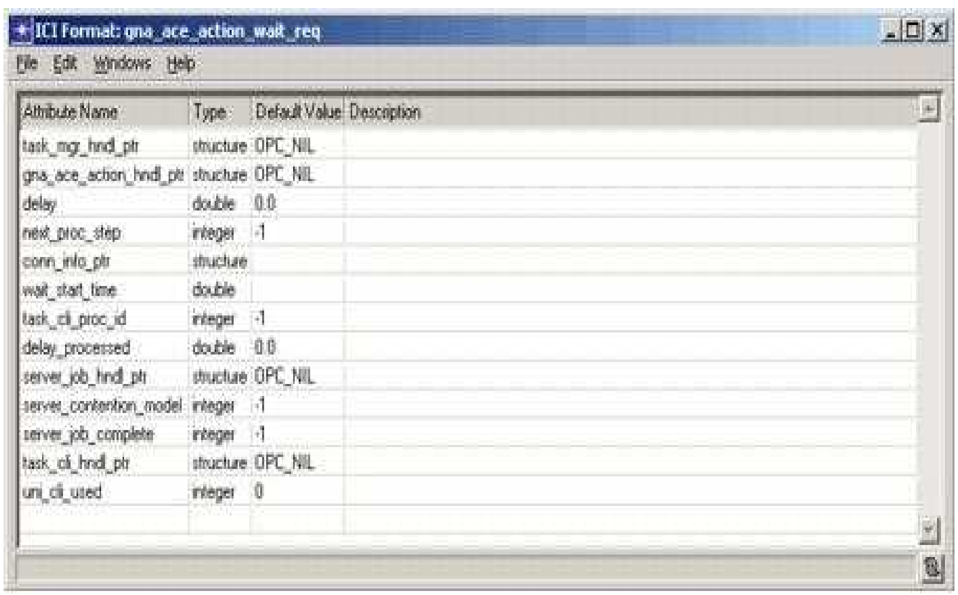
Link Model Editor creates new types of link objects. Each new type of link can have different attribute interfaces and representation. It is also possible to edit and view link models already created.

Packet Format Editor

Develop packet formats models are created by using Packet Format Editor. This editor defines the internal structure of a packet as a set of fields. A packet format contains one or more fields, represented in the editor as colored rectangular boxes. The size of the box is proportional to the number of bits specified as the field's size.

ICI Editor

ICI Editor is used to Create, edit, and view interface control information (ICI) formats. ICIs are used to communicate control information between processes.



Attribute Name	Type	Default Value	Description
task_mgr_hndl_ptr	structure	OPC_NIL	
gna_ace_action_hndl_ptr	structure	OPC_NIL	
delay	double	0.0	
next_proc_step	integer	-1	
conn_info_ptr	structure		
wait_start_time	double		
task_cli_proc_id	integer	-1	
delay_processed	double	0.0	
server_job_hndl_ptr	structure	OPC_NIL	
server_contention_model	integer	-1	
server_job_complete	integer	-1	
task_cli_hndl_ptr	structure	OPC_NIL	
uni_cli_used	integer	0	

Figure 3.4 example of ICI editor

PDF Editor

The PDF (Probability Density Function) Editor describes the spread of probability over a range of possible outcomes. A PDF can model the likelihoods associated with packet interarrival times, or it can model the probability of transmission errors. This editor allows creating, editing, and viewing probability density functions (PDFs).

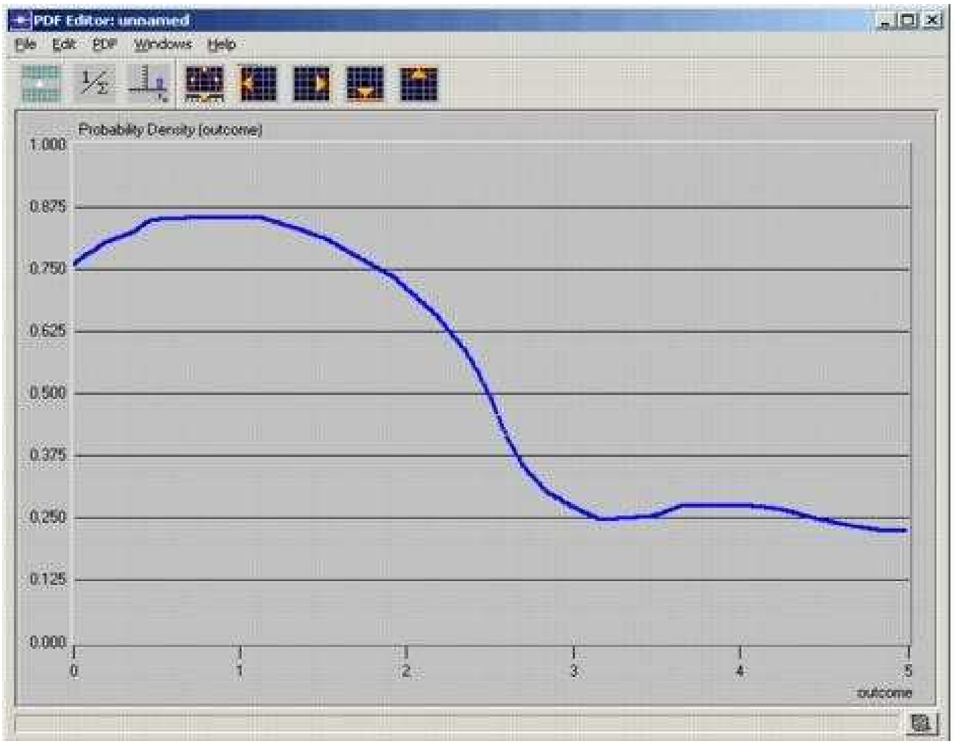


Figure 3.5 example of PDF editor

Path Editor

The Path Editor defines path models; each path object's underlying model determines its attribute interfaces, presentation, and behavior.

Demand Editor

The Demand Editor defines demand models; each demand object's underlying model determines its attribute interfaces, presentation, and behavior.

Link Editor

The Link Editor supports the definition of reusable link models that are used to create link objects in the Project Editor. Each link object's attribute interfaces, presentation, and behavior, are determined by the link model that it relies upon.

Once all the different interfaces are shown, it is necessary to describe the different steps to build a network model and to simulate it. For the purposes of this thesis work, it's only necessary to work with the project.

3.3 The Modeler Workflow

This section outlines the workflow when using OPNET.

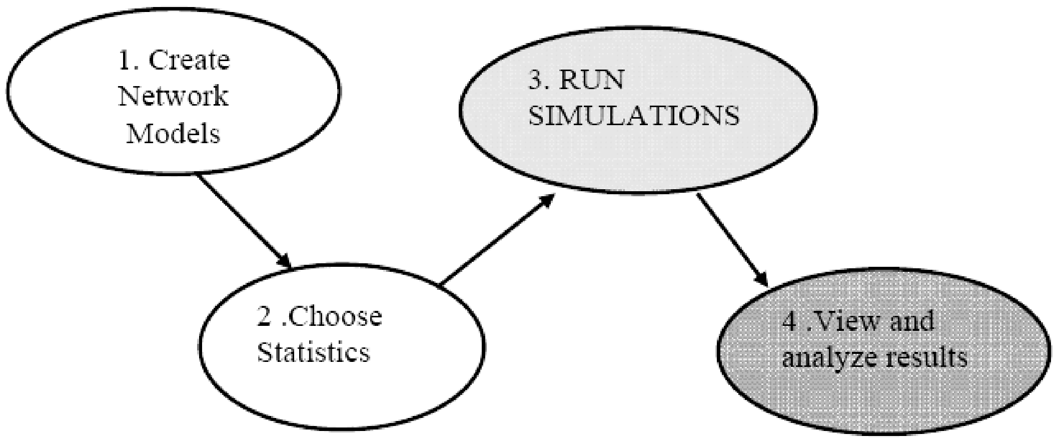


Figure 3.6 Workflow Model

3.3.1 Create Network Model

The first step is to create the networks models. It is necessary to generate the network to simulate in any of the following three ways:

- Placing individual nodes from the object palette into the workspace.
- Using the rapid configuration tool.
- And/or importing the network from an external data.

Furthermore, you have to introduce the traffic you want to run through the network. There is two main ways of putting traffic in the model:

a) Importing

b) Manually specifying

3.3.2 Choose Statistics

Afterwards and before running a simulation, it is necessary to choose the statistics we want to collect. OPNET does not automatically collect all statistics in the system because there are so many available that you may not have enough disk space to store them. Specifying statistics is a straightforward task which is performed through the GUI.

3.3.3 Run Simulation

The third thing to set is configuring the parameters of the simulation and running them. Running simulations is typically thought of as the next-to-last step in the simulation and modeling process, the last step being results analysis. However, simulation is typically done many times in the modeling process to check the rightness of the generated network. There are different kinds of analysis that can be done in OPNET MODELER.

1. Discrete Event Simulation
2. Flow Analysis
3. Failure Impact Analysis
4. NetDoctor Validation

Discrete event simulation provides the most detailed results but has the longest running times. This is because it does a more thorough analysis than the others, handling explicit traffic, conversation pair traffic, and link loads. The other types answer specific types of questions and generate results much faster than a discrete event simulation. A flow analysis, for example, handles only conversation pair traffic (flows) and a NetDoctor validation does not consider traffic at all. Licenses for generating Discrete Event Simulations (DES) are available for this studies and analysis.

3.3.4 View and Analyze Results

It is the last step of simulation. The results can be watched from the Project Editor or from the Analysis Tool. The Analysis Tool provides the capability to extract data from simulation output files, and to manipulate and display it according to various plotting methods. Data can be manipulated through built-in operations in a different way to get wanted information.

Hence, the final workflow of a project could be as follows:

• Create project

• Create baseline scenario

- Import or create topology
- Import or create traffic
- Choose results and reports to be collected

- View results and analyze them

Iterate by duplicating the scenario and changing parameters

OPNET uses a project and scenario approach to model networks. Project is a collection of related network scenarios in which each explores a different aspect of network design.

A project contains at least one scenario and a scenario is a single instance of a network containing all the information. It is possible to run all the scenarios of the network at the same time and compare the results of each one. This allows the scenarios to check if a server will support and increment of the traffic, the effect of the increment of the traffic in a link in the response of a service, etc [14].

CHAPTER 4: Simulation Results and Discussions

4.1 Introduction

I have studied various Medium Access Control protocols for Wireless local Area Networks. To choose the best one amongst the existing protocols, it is necessary to have a network model scenario and some performance metrics on the basis of which they can be evaluated. In this chapter, various metrics for comparing the performance of MAC protocols and a network model to carry out simulation is discussed. At the end of this chapter, results obtained from the simulation in the form of graphs will be presented. Future work is also suggested.

4.2 Metrics

Selecting the correct metrics in the evaluation of the QoS mechanisms is vital to the result and validity of the evaluation. The metrics used are Throughput, Access Delay, and End to End Delay in case of realtime multimedia traffic like VoIP, Video streaming (Video conferencing), response time in case of Telnet or Remote Login type applications which cannot tolerate delay and loss of data and Retransmission Attempts in case a station does not get a chance due to internal collision. Following is the list of metrics used:

Throughput

The Throughput for different priority levels shows how well the QoS schemes can provide service differentiation between the various priorities. The Throughput of all stations shows the utilization of the wireless medium. Wireless bandwidth is a scarce resource, so efficient use of it is vital.

Media Access Delay

We measure access delay as the time from when the data reaches the MAC layer until it is successfully transmitted out on the wireless medium. The reason for studying average access delay is that many real-time applications have a maximum tolerable delay, after which the data will be useless. Therefore, it is important to provide low delay for real-time flows.

Retransmission Attempts

Total number of Retransmission Attempts by all WLAN MACs in the network until either packet is successfully transmitted or it is discarded as a result of reaching short or long retry limit. For 802.11e-capable MACs, the Retransmission Attempt counts recorded under this statistic also include retry count increments due to internal collisions. This factor plays important role in Performance of WLAN.

Data Dropped

Data Dropped due to unavailability of access to medium. This factor largely affects the reliability of WLAN.

4.3 Simulation Scenario

Creating a simulation scenario that is equivalent to real world scenario is the first step of simulation. In this simulation, the wireless topology consisted of several wireless stations and one base station in the wireless LAN. The base station was connected to a wired node (Figure 4.1) which serves as a sink for the flows from the wireless domain. All wireless stations are located such that every station is able to detect a transmission from any other station, and there is no mobility in the system. This means our results will not be impacted by mobility and phenomenon such as the hidden node problem.

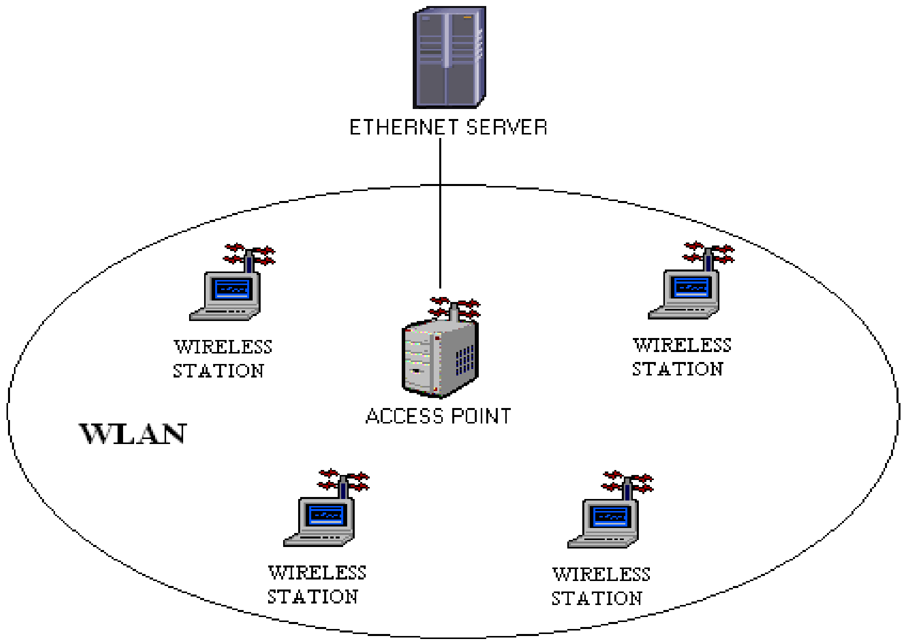


Figure 4.1 a sample network model

The simulation experiments are carried out using OPNET Simulator (version 14.0) on Windows platform. For this simulation, a data rate of 11 Mbps is chosen. The various MAC and PHY parameter values used in our experiment are according to IEEE 802.11e default values given in Table 4.1. We have run the simulation for 5 minutes for each scenario, then compared the results obtained from them. Figure 4.1 shows a sample network model for our experiment.

Table 4.1: MAC and PHY parameter values used in Experiment

ATTRIBUTE	VALUE
Physical Characteristics	Direct Sequence
Data Rate (bps)	11 Mbps
Transmit Power (W)	0.005
Buffer Size (bits)	256000
BSS Identifier	Auto Assigned
Channel settings	Auto Assigned
Roaming Capability	Disabled
AP Beacon Interval (secs)	0.02
Large Packet Processing	Drop

4.4 Simulation Method

To compare the performance of DCF and EDCF two scenarios were created; medium access in first scenario was supported by DCF and in second, EDCF protocol was used at the MAC layer. Network environment factors which were used as a benchmark configured same for both scenarios. Detailed specifications are given in the Table 4.1 showing the MAC and PHY parameters used in experiment. The performance evaluation is done by simulating both scenarios one by one in OPNET simulator and then comparing the graphs obtained.

4.5 Results

After choosing metrics, the simulation is done for 5 minutes for a scenario. Then results were gathered.

4.5.1 Analysis of EDCF

In case of EDCF, all four traffic classes were fed into the MAC layer from higher layer, which are corresponding to AC(0), AC(1), AC(2) and AC(3) respectively to check how efficient the new protocol is to provide service differentiation required for real time application. (Note that DCF does not support service differentiation, so no provision of Access category). For this, in the application profile of scenario (for EDCF protocol) different application was configured for different access category. Details are shown in the Table 4.2.

Table 4.2 Access Category corresponding to an application

ACCESS CATEGORY	**APPLICATION CONFIGURED**	**DESIGNATION**
AC(0)	HTTP (LIGHT)	BACKGROUND
AC(1)	REMOTE LOGIN (HEAVY)	EXCELLENT EFFORT
AC(2)	VIDEO CONFERENCING	INTERACTIVE MULTIMEDIA
AC(3)	VOIP	INTERACTIVE VOICE

In the profile configuration, a profile for clients was configured that uses all the four applications. In simulation scenario, 15 stations were configured to use these services randomly. In the simulation, we assumed that each traffic class has the equal portion of the total data traffic in terms of the average number of packets generated per unit time. The results obtained are as follows:

4.5.1.1 Throughput of Different Access Categories

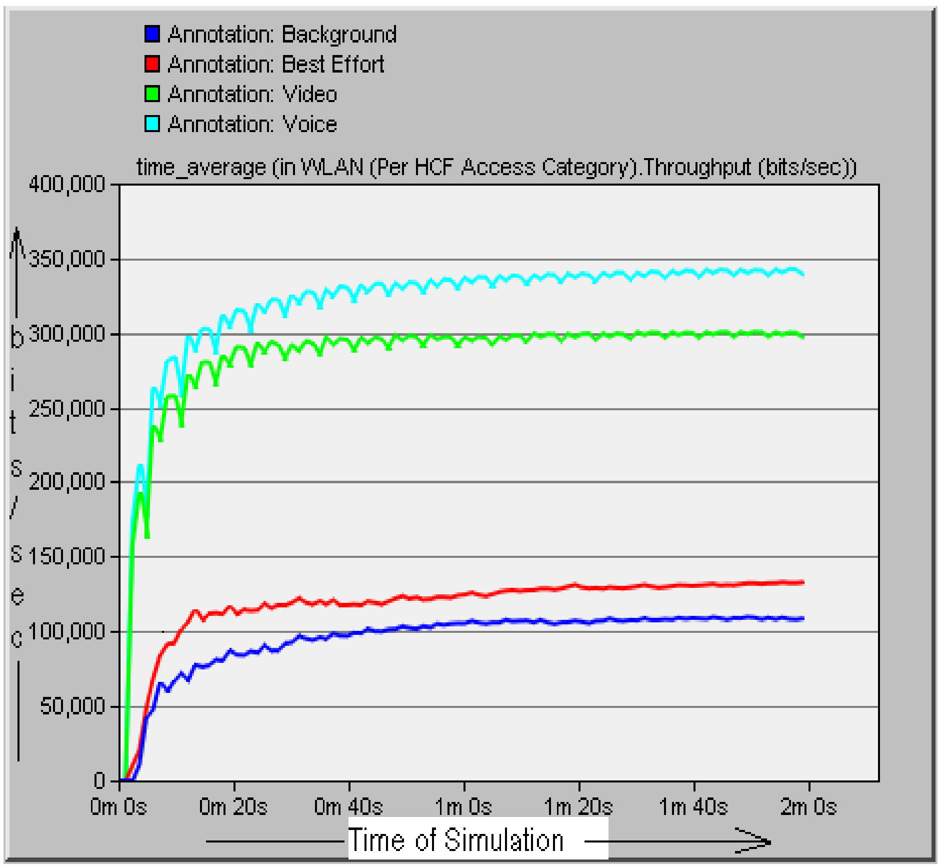


Figure 4.2 Throughput of Different Access Categories

It is observed from figure 4.2 that the Throughput of Access category 3 is way high than the Access category 0 and 1. Throughput for Access category 2 lies in between 3 and 1. It means that Throughput for applications like Voice over IP and Video conferencing, EDCF provides maximum Throughput by providing them more priority over the other services like simple HTTP.

4.5.1.2 Media Access Delay for Different Access Categories

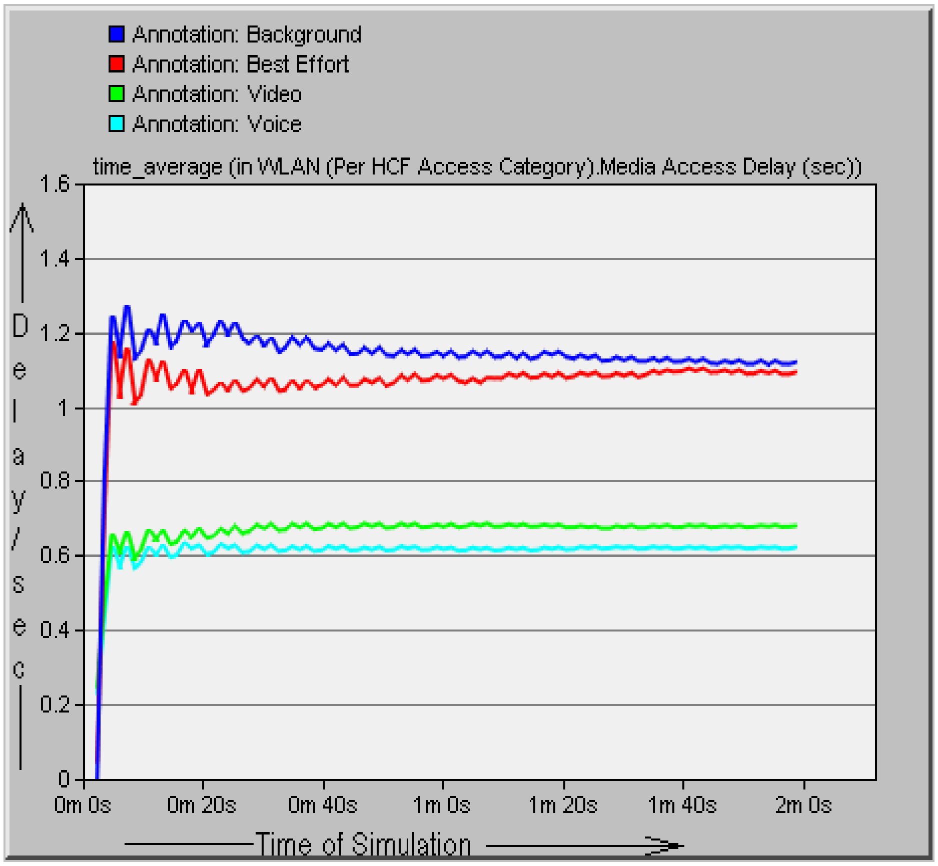


Figure 4.3 Wireless LAN - Media Access Delay

It is observed from figure 4.3 that the Media Access Delay for Access category 3 is minimum among all Access categories. Media Access Delay for Access category 2 is just 3 to 4 seconds more than AC (3). It means that the medium is assigned to the application according to the priority. Thus, EDCF provides lesser Medium Access Delay for realtime applications.

4.5.2 Comparative Analysis of DCF and EDCF

Next step is to check the performance of both protocols in terms of Throughput, Media Access Delay, Retransmission Attempts and Data Dropped. These four metrics are determining factors in terms of overall performance of both the protocols.

4.5.2.1 Throughput

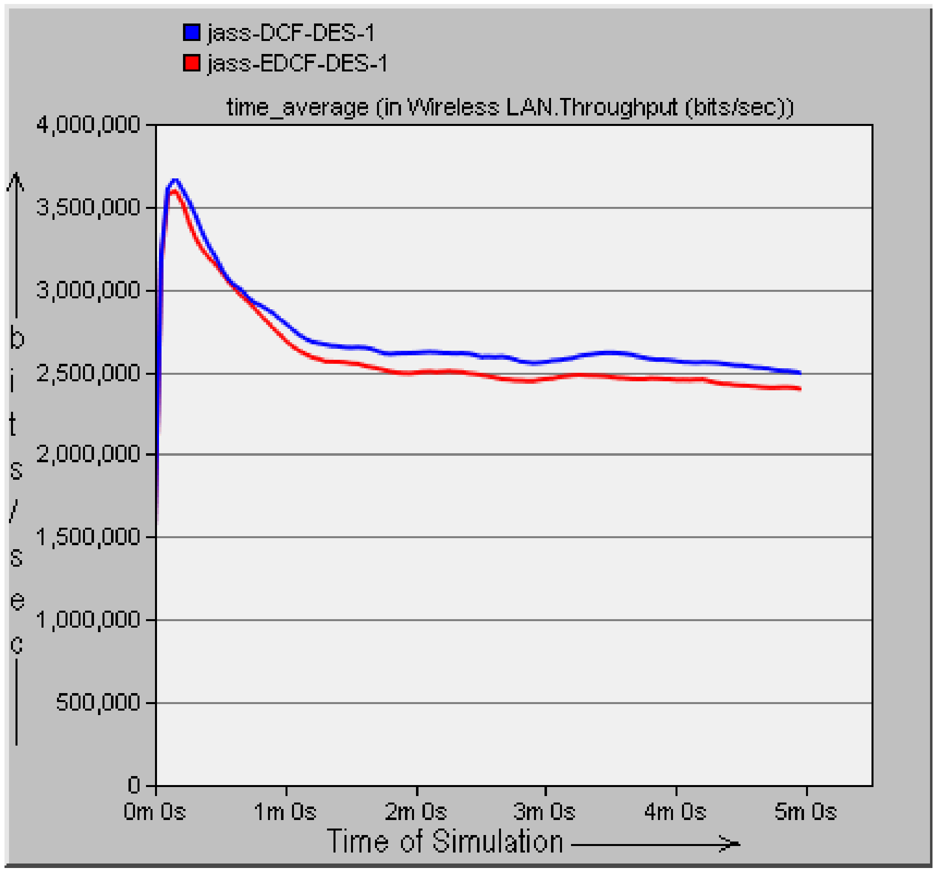


Figure 4.4 Throughput of DCF vs. EDCF

It is observed from figure 4.4 that in the first 30 seconds of simulation, Throughput of both DCF and EDCF is high, but then after that, it decreases with time and stabilizes for both protocols. Throughput in first 30 seconds is high due to less number of Retransmission Attempts (less number of backoff's). From Graph analysis, one fact is clearly visible, that curve of DCF is marginally higher than that of EDCF. We can conclude that DCF's overall Throughput is somewhat more than the EDCF.

4.5.2.2 Retransmission Attempts

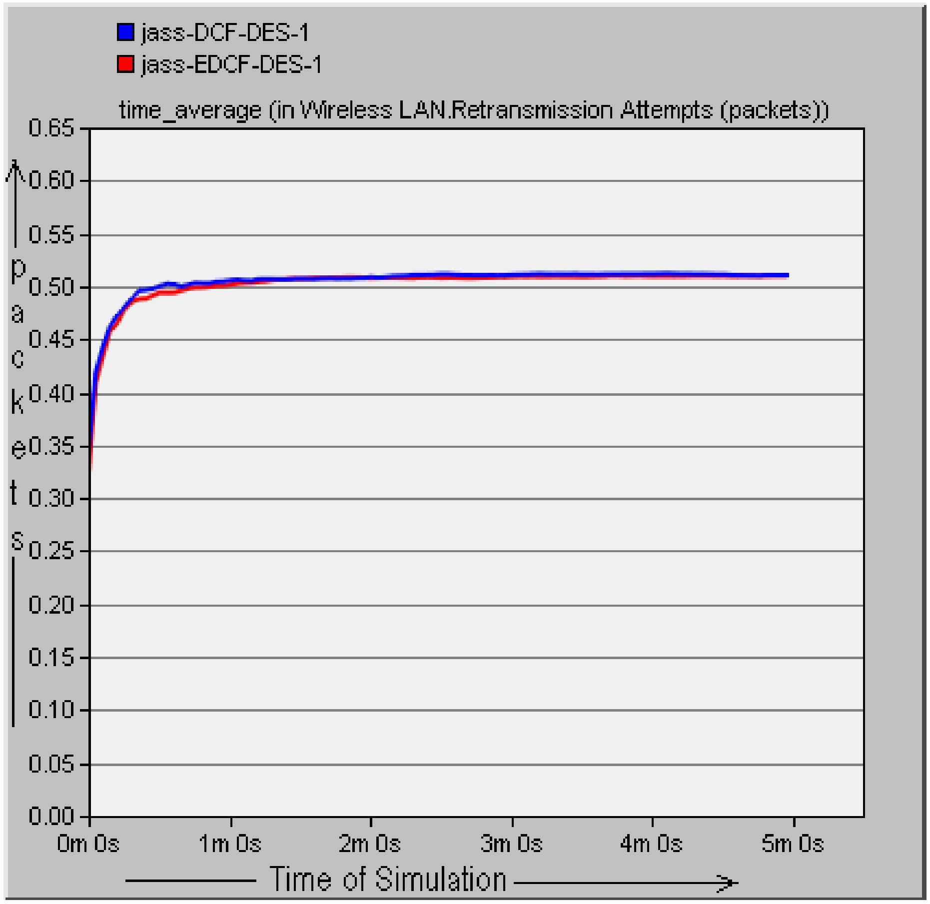


Figure 4.5 Retransmission Attempts of DCF vs. EDCF

It is observed from figure 4.5 that in the first 30 seconds of simulation, Retransmission Attempts for both DCF and EDCF are less, but then after that, it decreases with time and stabilizes for both protocols. Retransmission Attempts in first 30 seconds are less due to less number of backoff's assigned to wireless stations. There is a small noticeable difference between curves of Retransmission Attempts of DCF and EDCF protocol. That small difference implies that the overall Retransmission Attempts made in DCF protocols are a bit lesser than EDCF protocol.

4.5.2.3 Media Access Delay

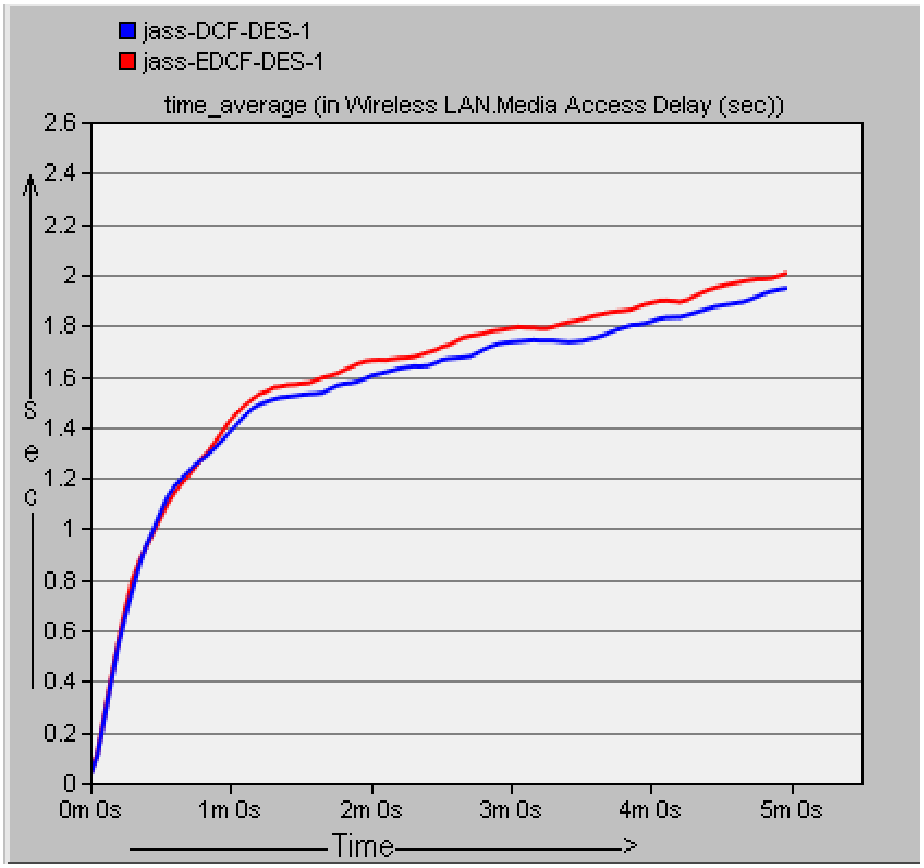


Figure 4.6 Media Access Delay of DCF vs. EDCF

In Figure 4.6, for the first minute of simulation the Medium Access Delay for both protocols increases at equal pace, and then after that, DCF suffers somewhat lesser Access Delay than EDCF. The increase in the Medium Access Delay for both protocols is due to increase in the number of nodes competing to gain access of medium.

4.5.2.4 Data Dropped

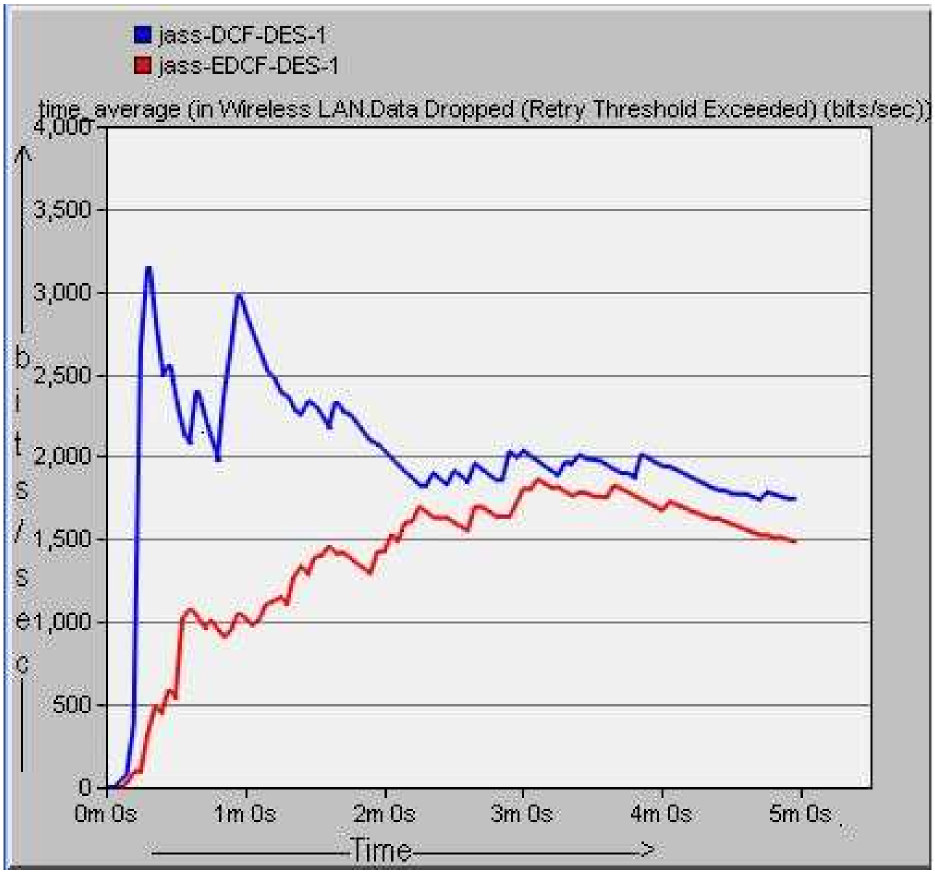


Figure 4.7 amount of Data Dropped of DCF vs. EDCF

It is observed from figure 4.7 that the first 30 seconds of simulation, DCF suffers a sudden high Data Drop, but Data Drop in EDCF increases gradually. The reason of varying Data Drop gradually in EDCF is the service differentiation which provides priority based scheme to handle different kind of data. After 2.5 minutes of simulation, curves of Data Dropped of DCF and EDCF remain same for both protocols, EDCF finishes at less Data Dropped than DCF.

CHAPTER: 5 Conclusions and Future Scope

5.1 Conclusion

The results obtained from simulation shows that Enhanced Distribution Coordination Function provides efficient mechanism for service differentiation and hence provides quality of service to the Wireless LAN. However, this improvement comes at a cost of a decrease in quality of the lower priority traffic up to the point of starvation. The acquisition of the radio channel by the higher priority traffic is much more aggressive than for the lower priority. Higher priority traffic benefited, while lower priority traffic suffered. In terms of overall performance (under the used simulation conditions in this particular study of QoS of Wireless LAN), DCF performs marginally well than EDCF. This happens due to reason that in EDCF mechanism, each AC function acts like a virtual station for medium access, so more collision will be expected for EDCF scenario. But in terms of Quality of Service for realtime applications (like Video conferencing) EDCF outperforms DCF. EDCF has been purposed as the medium access control protocol for IEEE’s upcoming standard IEEE 802.11e. The wireless devices using EDCF as MAC protocol would be available in market in the next coming two years. Presently, all of the wireless devices use DCF as the default MAC protocol and PCF as the optional functionality.

5.2 Future Work

Future work may be done to minimize collisions that occur in EDCF and also to introduce a procedure to avoid the starvation of lower priority processes.

References

[1] Choi Sunghyun, Del, Sai, Mangold S. "IEEE 802.11 e contention-based channel access (EDCF) performance evaluation", IEEE International Conference on In Communications, vol. 2, pp. 1151-1156, 2003.

[2] Choi S. and Shin K. G., "A cellular local area network with QoS guarantees for heterogeneous traffic", Proceedings IEEE Infocom'97, pp. 1032-1039, Kobe, Japan, April 1997.

[3] Crow Brian P., Widjaja Indra, Kim Jeong Geun, Prescott T. Sakai,"IEEE 802.11 Wireless Local Area Networks", IEEE Communications Magazine, September 1997.

[4] Draft Standard IEEE 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", November 1999.

[5] Grilo A. and Nunes M., "Performance Evaluation of IEEE 802.11e", In Proc. IEEE Personal, Indoor and Mobile Radio Communications (PIMRC), vol. 1, pp. 511 -517, September 2002.

[6] Gu D. and Zhang J., "QoS enhancement in IEEE 802.11 wireless local area networks", IEEE Communications Magazine, vol. 41, no. 6, pp. 120 -124, June 2003.

[7] Hannikainen Marko, Lavikko Tommi, Kukkala Petri And Hamalainen Timo D., "QoS Supporting Wireless Network", published in Kluwer Academic Publishers., 2003.

[8] Kim Andrew, "OPNET Tutorial", TECOMM LAB, March 2003.

[9] Lindgren Anders, Almquist Andreas, and Schelen Olov,"Quality of Service Schemes for IEEE 802.11", 2001.

[10] Liu X., Chong E. K. P., and Shroff N. B., “Opportunistic Scheduling with QoS Requirements in Time-varying Wireless Channels", Computer Networks, vol. 4, no. 41, pp. 451-474, March 2003.

[11] Networking Guide: Physical Media - radio (RF), microwave, infrared http://www.conniq.com/Networking_Media5.htm.

[12] OPNET LABS, “Creating Wireless Network”, 2006.

[13] Peterson Roger L., Ziemer Rodger E. and Borth David E., “Introduction to Spread-Spectrum Communications”, Prentice Hall, 1995.

[14] Prokkola Jarmo, “OPNET - Network Simulator”, seminar presented at VTT Technical Research Centre of Finland, March, 2006.

[15] Puschita E., Palade T., Pitic R. "Wireless LAN Medium Access Techniques QoS perspective", Signals, Circuits and Systems, ISSCS 2005. International Symposium vol. 1, pp. 267- 270, July 2005.

[16] Rajaraman Rajmohan, “Wireless Networks”, Pearson Edu,2005.

[17] Schiller J., “Mobile Communication”, 2nd Edition, Pearson.Edu, 2007.

[18] Schwaderer Curtis A., “Wireless networks: Past, present, and a very bright future”, Web site at www.ivifoundation.org

[19] Siddique Mohammad M., Konsgen Andreas, ”Advanced Communication Lab Opnet Tutorial”, 2006.

[20] Siddique Mohammad M., Konsgen Andreas, “WLAN Lab Opnet Tutorial”, University Bermen Press, 2007.

[21] Sobrinho J. L. and Krishnakumar A S., “Quality-Of-Service in ad hoc carrier sense multiple access networks”, IEEE Journal on Selected Areas in Communicmions, vol. 17, pp. 1353-1368, August 1999.

[22] Sobrinho Joao L., Krishnakumar A. S., “Quality-of-Service in Ad Hoc Carrier Sense Multiple Access Wireless Networks”, IEEE journal on selected areas in communications, vol. 17, no. 8, august 1999.

[23] Stajmenovic Ivan, “Handbook of Wireless Networks and Mobile Computing”, Wiley Publications, India, 2002.

[24] Suzuki T. and Tasaka S., "Performance evaluation of priority-based multimedia transmission with the PCF in an IEEE 802.11 standard wireless LAN", in In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), vol. 2, pp. G-70 - G-77,September - October 2001.

[25] Vaidya Nitin H. and Bahl Paramvir and Gupta Seema "Distributed Fair Scheduling in a Wireless LAN", IEEE transactions on mobile computing, vol. 4, no. 6, pp. 167-178, nov. 2005.

[26] Venkatakrishnan Balasubramanian Appiah, Selvakennedy S., **“**An enhanced HCF for IEEE 802.11e wireless networks”, International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems, vol-1 pp. 135-142, 2004.

[27] Xi Weihua Helen, Whitley Toby, Munro Alistair, Barton Michael, “Modeling and Simulation of MAC for QoS in IEEE 802.11 Using OPNET Modeler”, Networks &J Protocols Group, CCR, 2006.

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