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A Differentiated Services Architecture for Quality of Service Provisioning in Wireless Local Area Networks

by

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BSc (Eng)

A thesis submitted to the Dublin Institute of Technology
for the degree of

Master of Philosophy

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School of Electronic and Communications Engineering

March 2004

Declaration

I certify that this thesis which I now submit for examination for the award of MPhil, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Tristan Raimondi

1st March 2004

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Finally, I thank my family and friends geographically near and far for their love and support.

Abstract

Currently the issue of Quality of Service (QoS) is a major problem in IP networks due to the growth in multimedia traffic (e.g. voice and video applications) and therefore many mechanisms like IntServ, DiffServ, etc. have been proposed. Since the IEEE 802.11b (or Wi-Fi) standard was approved in 1999, it has gained in popularity to become the leading Wireless Local Area Network (WLAN) technology with millions of such networks deployed worldwide. Wireless networks have a limited capacity (11 Mbit/s in the case of Wi-Fi networks) owing to the limited amount of frequency spectrum available. At any given time there may be a large number of users contending for access which results in the bandwidth available to each user being severely limited. Moreover, the system does not differentiate between traffic types which means that all traffic, regardless of its importance or priority, experiences the same QoS. An important network application requiring QoS guarantees is the provision of time-bounded services, such as voice over IP and video streaming, where the combination of packet delay, jitter and packet loss will impact on the perceived QoS. Consequently, this has led to a large amount of research work focussing mainly on QoS enhancement schemes for the 802.11 MAC mechanism. The Task Group E of the IEEE 802.11 working group has been developing an extension to the Wi-Fi standard that proposes to make changes to the MAC mechanism to support applications with QoS requirements. The 802.11e QoS standard is currently undergoing final revisions before approval expected sometime in 2004. As 802.11e WLAN equipment is not yet available, performance reports can only be based upon simulation. The objective of this thesis was to develop a computer simulator that implements the upcoming IEEE 802.11e standard and to use this simulator to evaluate the QoS performance enhancement potential of 802.11e. This thesis discusses the QoS facilities, analyses the MAC protocol enhancements and compares them with the original 802.11 standard. The issue of QoS provisioning is primarily concerned with providing predictable performance guarantees with regard to throughput, packet delay, jitter and packet loss. The simulated results indicate that the proposed QoS enhancements to the MAC will considerably improve QoS performance in 802.11b WLANs. However, in order for the proposed 802.11e QoS mechanism to be effective, the 802.11e parameters will need to be continually adjusted in order to ensure QoS guarantees are fulfilled for all traffic loads.

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Abbreviations and acronyms

AC	Access Category
ACK	Acknowledgment
AEDCF	Adaptive Enhanced Distributed Coordination Function
AIFS	Arbitration Inter Frame Spacing
AIFSN	Arbitration Inter Frame Spacing Number
AP	Access Point
BC	Backoff Counter
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
BW_{access}	Access Bandwidth
BW_{free}	Free Bandwidth
BW_{idle}	Idle Bandwidth
BW_{load}	Load Bandwidth
CAP	Controlled Access Phase
CCI	Controlled Contention Interval
CCK	Complementary Code Keying
CFP	Contention-Free Period
CP	Contention Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear To Send
CW	Contention Window
CW_{min}	The Minimum Size of CW
CW_{max}	The Maximum Size of CW
DCF	Distributed Coordination Function
DFS	Distributed Fair Scheduling
DIFS	DCF Inter Frame Space
DS	Distribution System
DSSS	Direct-Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
EWMA	Exponentially Weighted Moving Average
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
FIFO	First In First Out
HC	Hybrid Coordinator

HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordinator Function
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter Frame Space
ISM	Industrial, Scientific and Medical
ISO	International Standards Organization
LLC	Logical Link Control
MAC	Medium Access Control
MF	Multiplication Factor
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector
nQAP	non-QoS Access Point
nQBSS	non-QoS Basic Service Set
nQSTA	non-QoS Station
OFDM	Orthogonal Frequency-Division Multiplexing
PC	Point Coordinator
PCF	Point Coordinator Function
PHY	Physical Layer
PIFS	PCF Inter Frame Space
PLR	Packet Loss Rate
PPS	Packet Per Second
QPSK	Quadrature Phase Shift Keying
QAP	QoS Access Point
QBSS	QoS Basic Service Set
QoS	Quality of Service
QSTA	QoS Station
RRC	Radio Resource Control
RTS	Request To Send
SCFQ	Self-Clocked Fair Queuing
SIFS	Short Inter Frame Space
STA	Station
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TS	Traffic Stream
TSPEC	Traffic Specification
TXOP	Transmission Opportunity
UDP	User Datagram Protocol
UP	User Priority
VoIP	Voice over Internet Protocol
WLAN	Wireless Local Area Network
Wi-Fi	Wireless Fidelity

Chapter 1

Introduction

The past few years have seen an explosion in the deployment of wireless networks due to their ease of installation and flexibility. The IEEE 802.11b WLANs are one of the most widely deployed wireless technologies and are likely to play a major role in multimedia home networks and next-generation wireless communications. The main characteristics of the IEEE 802.11b WLAN are its simplicity, scalability, robustness, reliability and cost effectiveness. The initial growth in WLAN deployment has been in enterprise networks as a supplement to traditional wired LANs. More recently, WLANs have seen enormous growth in home deployments. As WLANs become more widespread and begin to replace traditional wired Ethernet in many installations, it is natural that people expect them to support the same applications. However the wireless medium has fundamentally different characteristics from a wired medium and previous research work shows that what works well in a wired network cannot be directly applied in a wireless network. Indeed QoS issues in wired Ethernet (e.g. 802.3) have been neglected due to the relative ease with which the physical layer bandwidth has improved (1Gbit/s is now a common link speed between switches in enterprise LANs). In wireless environments, bandwidth is scarce and channel conditions are time varying and sometimes highly lossy which makes physical layer data rate improvements more difficult to achieve.

Indeed wireless networks have a limited capacity (11 Mbit/s in the case of Wi-Fi networks) owing to the limited amount of frequency spectrum available. At any given time there may be a large number of users contending for access which results in the bandwidth available to each user being severely limited. While the original IEEE 802.11 DCF (Distributed Coordination Function) channel access function may provide satisfactory performance in delivering best-effort traffic, it does not have any provision to support QoS, i.e. all data traffic is treated in a best-effort manner. An important network application requiring QoS guarantees is the provision of time-bounded services, such as Voice over IP (VoIP) and video streaming which a require specified bandwidth allocation and where the combination of packet delay, jitter and packet loss will impact on the perceived QoS. Moreover in DCF operation, all stations contend for the wireless medium with the same priority. There is no differentiation between traffic types to support traffic with QoS requirements therefore all traffic, regardless of its importance or priority, experiences the same QoS.

Consequently these issues have led to a large amount of research work focussing mainly on QoS enhancement schemes for the 802.11 MAC mechanism [2][3][4][5][6]. At the same time Task Group E of the IEEE 802.11 working group has been developing an extension to the Wi-Fi standard, known as IEEE 802.11e [7], that proposes to make changes to the MAC mechanism to support applications with QoS requirements. The QoS facility includes an additional coordination function called the Hybrid Coordination Function (HCF) that is used to support parameterized IntServ QoS services. The HCF uses both a contention-based channel access function, called the Enhanced Distributed Channel Access (EDCA) mechanism for contention-based access and HCF Controlled Channel Access (HCCA) based on a polling mechanism for contention-free access. HCF combines and enhances aspects of the contention-based and contention-free access methods to provide QoS stations with prioritized DiffServ and parameterized IntServ QoS access to the wireless medium, while continuing to support non-QoS stations for best-effort data transfer. The HCF is compatible with the Distributed Coordination Function (DCF) and may also optionally contain the Point Coordination Function (PCF).

As with the original 802.11 MAC, the 802.11e enhancements are designed to work with all possible 802.11 physical layers, the original 802.11, 802.11b, 802.11a and 802.11g. The 802.11 WLAN standards operates in the unlicensed 2.4 GHz and 5 GHz Industrial, Scientific and Medical (ISM) bands. The 802.11b PHY amendment is an extension to the original 802.11 Direct-Sequence Spread Spectrum (DSSS) PHY and supports up to 11 Mbit/s data rate and is currently the most widely deployed WLAN technology. Another PHY amendment, 802.11a, supports up to 54 Mbit/s using Orthogonal Frequency-Division Multiplexing (OFDM) modulation techniques and operates in the 5 GHz band. Although 802.11a supports higher data rates, it is not as widely deployed yet, as it is a later standard than 802.11b and uses the 5 GHz band which has different availability worldwide. A new PHY amendment, 802.11g has just been ratified which achieves significantly higher data rates than 802.11b in the 2.4 GHz band using OFDM modulation. It also seems to be more robust than 802.11a, mainly due to better propagation characteristics in the 2.4 GHz band [8].

The proposed 802.11e QoS standard is currently undergoing final revisions by the IEEE for approval sometime in 2004 with equipment becoming available around the same time. As 802.11e WLAN equipment is not yet available, performance studies can only be based upon simulation. Consequently we propose a computer simulation model that faithfully implements the latest draft of the 802.11e standard [7]. The simulator was developed in C/C++ and essentially implements the 802.11e MAC mechanism. We simulated the contention-based channel access EDCA mechanism only and have implemented FIFO buffers in every station which allow us to calculate throughput, packet delay, jitter and packet loss which are important statistics when measuring and monitoring the level of QoS experienced by stations. The simulator was tested using performance results from published papers on the 802.11e standard to ensure correct implementation of the standard by the simulator. After being completely satisfied with the correct operation of the simulator, traffic engineering tests were carried out with regard to throughput and packet loss. The objective here was to identify the effects of varying the 802.11e parameters on performance. From the range of tuneable parameters that 802.11e offers, we have identified the two most important parameters for QoS provisioning, namely the Arbitration Inter Frame Spacing (AIFS) which is the minimum time interval between the wireless medium becoming idle and the start of transmission of a frame and the size of the Contention

Window (CW) from which a random number is drawn as part of the access mechanism. As a result of these tests a good understanding of the effects of these two parameters on performance was achieved.

By combining the effects of these two 802.11e parameters on QoS provisioning we have devised a set of design rules for establishing a class-based differentiated service QoS scheme comprising three QoS classes (e.g. a Gold class, a Silver class and a Bronze class of service). We show how AIFS may be used to set the class boundaries while CW_{min} is used to differentiate between stations within a class. The set of design rules ensures that at all times all stations belonging to a higher priority class (irrespective of the number of stations, traffic types, network load conditions, etc.) should always experience a better service than stations belonging to lower priority classes. We use a worked example to illustrate how these design rules might be applied.

This class-based differentiated service QoS scheme could be usefully applied to a real world scenario, e.g. a hotspot service where the operator could offer its customers different levels of services, i.e. Gold, Silver and Bronze. A customer who pays a premium for the Gold service will have the highest priority in terms of receiving service over the other customers using lower (and usually cheaper) services.

An additional consideration in any such QoS scheme is that it is traffic load dependent which suggests that if the 802.11e mechanism is to be successfully deployed in a WLAN network (e.g. hotspot scenario) the 802.11e parameters will have to be continually updated to meet the changing load.

Despite these problems, we find the proposed 802.11e QoS standard (at least in the case of the EDCA mechanism) attractive because of its simplicity and its ability to provide QoS differentiation which is an important improvement over legacy DCF.

The thesis is organised as follow:

Chapter 2 describes the IEEE 802.11b and 802.11e standards in detail, identifies the important metrics to be investigated and outlines the simulation environment that we have used to simulate the EDCA mechanism.

Chapter 3 gives an overview of different QoS enhancement schemes that have been investigated. It introduces a useful and intuitive description of the MAC operation based upon the concept of MAC bandwidth components.

Chapter 4 describes the C/C++ computer simulator of the 802.11e MAC mechanism that forms the basis for this work.

Chapter 5 describes the simulations setup and presents the results of the simulations. Also a set of design guidelines are proposed for setting up a class-based differentiated service QoS scheme.

Chapter 6 presents a summary of the main findings and conclusions arising from the work. It also suggests areas of further research.

Chapter 2

Background

2.1 IEEE 802.11 Standard

The Institute of Electrical and Electronics Engineers (IEEE) ratified the original 802.11 specification in 1997 as the standard for wireless LANs [1]. This original version of 802.11 provides for 1 Mbit/s mandatory and 2 Mbit/s optional data rates and a set of fundamental signalling methods and other services. The most critical issue affecting WLAN demand has been limited throughput. The data rates supported by the original 802.11 standard were too slow to support most general business requirements. Recognising the critical need to support higher data transmission rates, the IEEE ratified in 1999 the 802.11b PHY extension to the standard for rates of up to 11 Mbit/s.

2.1.1 Protocol Stack

The 802.11 standard focuses on the bottom two levels of the ISO model.

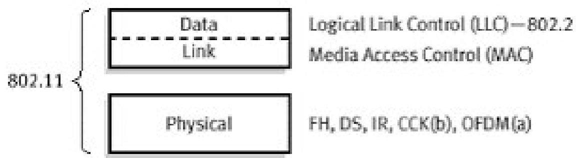

Figure 2.1 IEEE 802.11 Layers Description

The original 802.11 standard defines the basic architecture, features and services of 802.11b. The 802.11b specification affects only the physical layer (PHY), adding higher data rates and more robust connectivity.

2.1.2 802.11 Architecture

802.11 defines two pieces of equipment: A wireless station (STA) which is usually a PC equipped with a wireless network interface card and an Access Point (AP) which acts as a bridge between the wireless and wired networks.

An 802.11 WLAN is based on a cellular architecture where the system is subdivided into cells. Each cell is controlled by an AP which acts as the base station for the wireless network, aggregating access for multiple wireless STAs onto the wired network.

The 802.11 standard defines two modes: An infrastructure mode and ad-hoc mode. In infrastructure mode, the wireless network consists of at least one AP connected to the wired network called Distribution System (DS) and a set of wireless STAs. This configuration is called a Basic Service Set (BSS). An Extended Service Set (ESS) is a set of two or more BSSs forming a single subnet network.

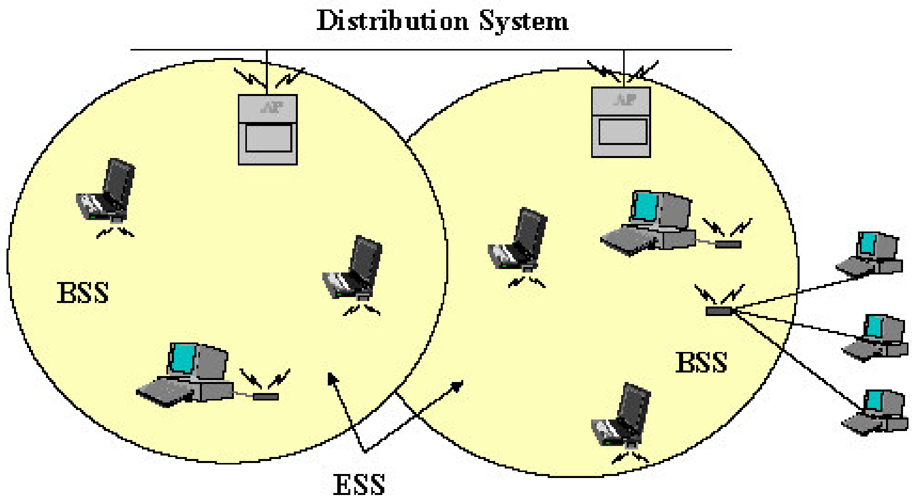

Figure 2.2 A Typical 802.11 WLAN

Ad hoc mode, also called peer-to-peer mode or an Independent Basic Service Set (IBSS) is simply a set of 802.11 wireless STAs that communicate directly with one another without using an AP or any connection to a wired network.

2.1.3 802.11 Physical Layer

The 802.11 physical layer includes two spread-spectrum radio techniques and a diffused infrared specification. The radio-based standards operate within the 2.4 GHz ISM band. These frequency bands are recognised by international regulatory agencies, such as the FCC (USA) and ETSI (Europe).

The 802.11 wireless standard defines data rates of 1 Mbit/s and 2 Mbit/s via radio waves using Frequency Hopping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS). It is important to note that FHSS and DSSS are fundamentally different signalling mechanisms and will not interoperate with one another.

Using the frequency hopping technique, the 2.4 GHz band is divided into 75 sub channels each of which is 1 MHz wide. The sender and receiver agree on a hopping pattern and data is sent over a sequence of the sub channels. Each conversation within the 802.11 network occurs over a different hopping pattern and the patterns are designed to minimize the chance of two senders using the same sub channel simultaneously.

In contrast, the direct sequence signalling technique divides the 2.4 GHz band into 14 channels each of which is 22 MHz wide. Adjacent channels overlap one another partially, with three of the 14 being completely non-overlapping. Data is sent across one of these 22 MHz channels without hopping to other channels. To compensate for noise on a given channel, a technique called "chipping" is used. This technique specifies an 11-bit chipping sequence called a "Barker sequence" to encode all data sent over the air.

Each 11-bit chipping sequence represents a single data bit and is converted to a waveform, called a symbol, that can be sent over the air. These symbols are transmitted at a 1 Msps (1 Million symbols per second) rate using a technique called Binary Phase Shift Keying (BPSK). In the case of 2 Mbit/s, a more sophisticated implementation called Quadrature Phase Shift Keying (QPSK) is used which doubles the data rate available in BPSK via improved efficiency in the use of the radio bandwidth.

2.1.4 802.11b Physical Layer

The 802.11b standard was developed in order to enable the physical layer to support two new speeds, 5.5 Mbit/s and 11 Mbit/s. To achieve this, DSSS had to be selected as the sole physical layer technique since FHSS cannot support higher speeds without violating the current FCC regulations. The implication is that 802.11b systems can only interoperate with 1 Mbit/s and 2 Mbit/s 802.11 DSSS systems and cannot work with the 1 Mbit/s and 2 Mbit/s 802.11 FHSS system.

To increase the data rate in the 802.11b standard, advanced coding techniques are employed. Rather than the two 11-bit Barker sequences, 802.11b specifies Complementary Code Keying (CCK) which consists of a set of 64 8-bit code words. The 5.5 Mbit/s rate employs CCK to encode 4 bits per carrier while the 11 Mbit/s rate encodes 8 bits per carrier. Both speeds use QPSK as the modulation technique and signal at 1.375 Mbit/s.

2.1.5 802.11 Data Link Layer

The data link layer consists of two sub-layers: Logical Link Control (LLC) and Medium Access Control (MAC). 802.11 operates the same as 802.2 LLC and uses 48-bit addressing as other 802 LANs, this allowing for simple bridging from wireless to wired networks.

2.1.6 MAC Layer

The MAC layer defines two channel access functions, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF).
The transmission medium can operate both in contention mode (DCF) and contention-free mode (PCF). The IEEE 802.11 MAC protocol provides two types of transmission: Asynchronous and synchronous. Asynchronous data transfer refers to traffic that is relatively insensitive to time delay (e.g. electronic mail and file transfers) and synchronous data transfer refers to traffic that is bounded by specified time delays to achieve an acceptable QoS, e.g. packetised voice and video streaming. The asynchronous type of transmission is provided by DCF which implements the basic access method of the 802.11 MAC protocol. DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and should be implemented in all the STAs. The synchronous service (also called contention-free service) is provided by PCF which basically implements a polling-based access method. The PCF uses a centralized polling approach which requires an Access Point (AP) that acts as a Point Coordinator (PC). The AP cyclically polls STAs to give them the opportunity to transmit the packets. Unlike the DCF, the implementation of the PCF is not mandatory. Furthermore, the PCF itself relies on the asynchronous service provided by the DCF.

2.1.7 Distributed Coordination Function (DCF)

The 802.11 MAC is similar in concept to 802.3, in that it is designed to support multiple users on a shared medium by having the sender sense the medium before accessing it. For 802.3 Ethernet LANs, the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol regulates how Ethernet STAs establish access to the wired medium and how they detect and handle collisions that occur when two or more devices try to simultaneously communicate over the LAN. In an 802.11 WLAN, collision detection is not possible, because a STA is unable to listen to the channel for collisions while transmitting. So 802.11 is a slightly modified protocol known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or DCF. CSMA/CA attempts to avoid collisions by using explicit packet acknowledgement (ACK) meaning an ACK packet is sent by the receiving STA to confirm that the data packet arrived intact.

Priority access to the wireless medium is controlled through the use of Inter Frame Space (IFS) time intervals between the transmissions of frames. The IFS intervals are mandatory periods of idle time on the transmission medium. Three IFS intervals are specified: Short IFS (SIFS), PCF-IFS (PIFS) and DCF-IFS (DIFS). The SIFS interval is the smallest IFS, followed by PIFS and DIFS respectively. STAs only required to transmit a SIFS have priority access over those STAs required to wait a PIFS or DIFS interval before transmitting.

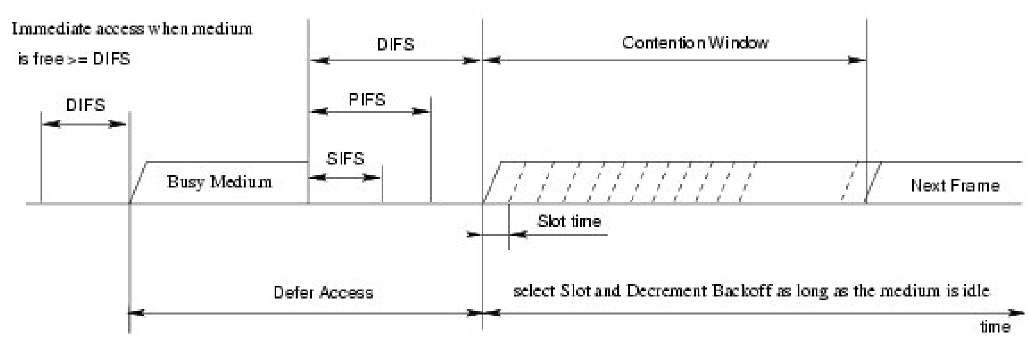

Figure 2.3 IFS Relationships of IEEE 802.11

2.1.7.1 Basic Access Method: CSMA/CA

DCF is a distributed medium access scheme. In this mode, a STA must sense the medium before initiating a packet transmission. If the medium is found idle for a time interval longer than Distributed Inter Frame Space (DIFS), then the STA can transmit the packet directly. Otherwise, the transmission is deferred and the backoff process is started (see Figure 2.4). Specifically, the STA computes a random time interval called Backoff Counter (BC), uniformly distributed between zero and the current Contention Window size (CW):

$$BC = rand[0, CW] \qquad \text{(equation 2.1)}$$

where:

$$CW_{min} < CW < CW_{max}$$

The BC is decreased only when the medium is idle, whereas it is frozen when another STA is transmitting. Each time the medium becomes idle, the STA waits for a DIFS and then continuously decrements the BC after every time slot. As soon as the BC reaches zero the STA is authorised to access the medium. Obviously, a collision occurs if two or more STAs start transmission simultaneously. The transmission of the ACK is initiated after a time interval equal to the SIFS after the end of the reception of the previous frame. Since the SIFS is smaller than the DIFS, the receiving STA does not need to sense the medium before transmitting an ACK. If the ACK is not received, the sender assumes that the transmitted frame was lost and schedules a retransmission and then enters the backoff process again. To reduce the probability of collisions, after each unsuccessful transmission attempt, the size of the contention window is doubled until a predefined maximum value CW_{max} is reached. To improve the channel utilization, after each successful transmission, the contention window is reset to a fixed minimum value CW_{min}.

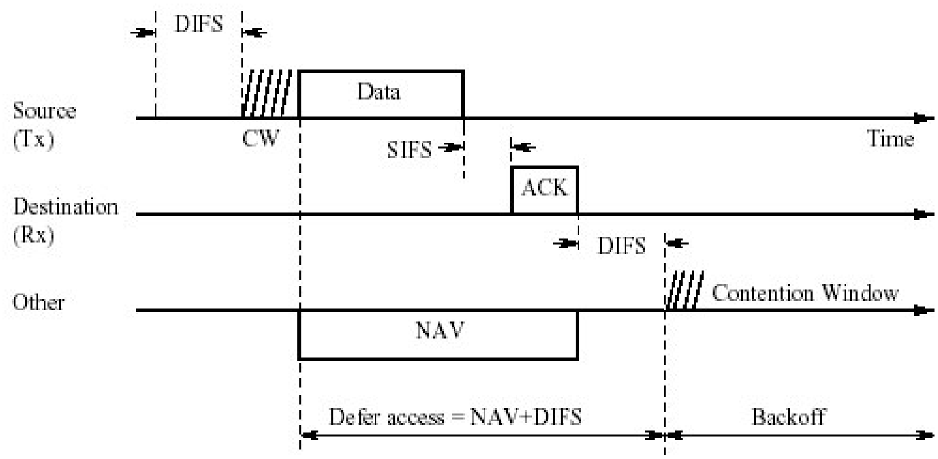

Figure 2.4 Basic DCF CSMA/CA Mechanism

In IEEE 802.11, carrier sensing is performed at both the air interface, referred to as physical carrier sensing and at the MAC sublayer, referred to as virtual carrier sensing. Physical carrier sensing detects the presence of other IEEE 802.11 WLAN users by analysing all detected packets and also detects activity in the channel via relative signal strength from other sources. virtual carrier sensing is described as follows.

2.1.7.2 Virtual Carrier Sense

A STA waiting to transmit a packet first transmits a short control packet called RTS (Request To Send) which includes the source, destination and the duration of the following transmission (i.e. the packet and the respective ACK). The destination STA then responds with a response control packet called CTS (Clear To Send) which includes the frame duration information.

All STAs receiving either the RTS and/or the CTS, set their virtual carrier sense indicator called NAV (Network Allocation Vector), for the given duration and use this information together with the physical carrier sense when sensing the medium. This mechanism also helps to combat the "hidden STA" problem, in which two STAs on opposite sides of an AP cannot hear activity from each other, usually due to distance or an obstruction. This helps in that it reduces the probability of a collision on the receiver that is caused by a "hidden STA" which can not "hear" the RTS from the transmitter but can "hear" the CTS and reserves the medium as busy until the end of the transmission. Conversely the RTS protects the transmitter area from collisions during the ACK from STAs that are out of range of the acknowledging STA.

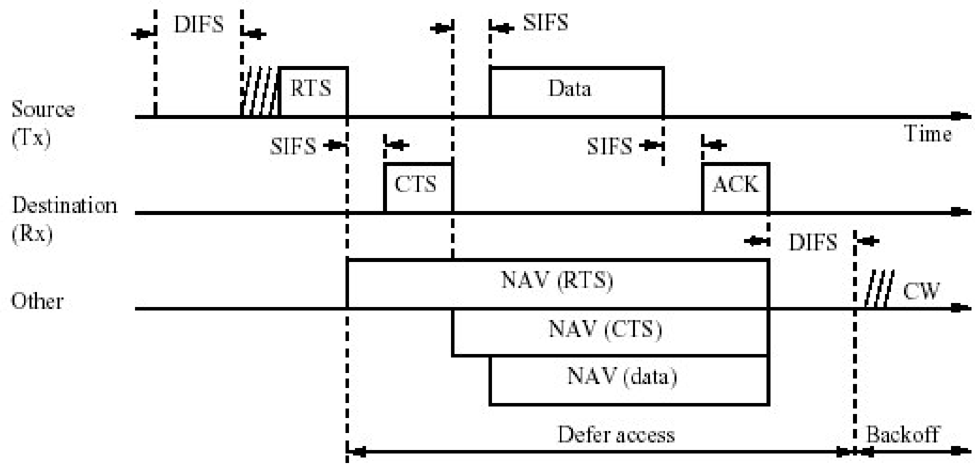

Figure 2.5 RTS/CTS Access Scheme

Since the RTS and CTS are short frames, the mechanism also reduces the overhead of collisions, since these are recognised faster then if the whole packet was to be transmitted. This is true if the packet is significantly larger than the RTS. However for small packet sizes, an additional delay is imposed by the overhead of the RTS/CTS frames, so the standard allows for short packets to be transmitted without the RTS/CTS transaction. This is controlled by a parameter called the RTS threshold. The decision to use the RTS/CTS is determined by the size of the packet to be transmitted, where the RTS threshold parameter sets the minimum packet size for invoking the RTS/CTS mechanism.

2.1.8 Point Coordination Function (PCF)

PCF is an optional channel access function in the 802.11 MAC specification which was intended to support time-bounded services such as voice and video. However, the PCF channel access function has never been implemented by any manufacturers of WLAN equipment. Unlike the DCF mode where control is distributed across all STAs, in the PCF mode a Point Coordinator (PC) collocated with an Access Point (AP) controls access to the media. If a BSS is set up with PCF-enabled, the two access functions (DCF and PCF) alternate, with a Contention-Free Period (CFP) followed by a Contention Period (CP) (see Figure 2.6). During the PCF mode, the PC maintains a list of registered STAs and polls each STA one by one according to the list. No STA is allowed to transmit unless it is polled and STAs receive data from the AP only when they are polled. Since PCF gives every STA in turn an opportunity to transmit in a predetermined order, a maximum latency is bounded. However, PCF is not scalable. A single AP dominates and controls medium access and it must poll all the STAs which can be ineffective in large networks. Moreover, all the traffic must go through the AP which wastes much bandwidth. The PCF is defined as an optional capability which needs a PC to initiate and control the CFP. The PC first senses the channel for a PIFS interval (PCF Inter Frame Space) and then starts a CFP by broadcasting a beacon signal. Note that PIFS is shorter than DIFS which allows the AP to gain control from the DCF mode and no DCF STAs are able to interrupt the operation of PCF mode. All STAs add *CFPmaxduration* (the maximum possible duration of the contention-free period) to their own NAVs which prevents them from taking control of the medium during CFP. Then, active users with time-bounded packet streams are periodically polled by the PC. The PC can terminate the CFP at any time by transmitting a CF-end packet which occurs frequently when the network is lightly loaded. When a terminal's turn in the polling list comes, the PC sends a buffered data packet to it, piggybacked with a CF-Poll or an ACK for the previous transmission. The receiver sends back an ACK or any buffered data, piggybacked with an ACK after a SIFS interval. Indeed, piggybacking can improve the channel utilisation greatly in PCF mode. Normally PCF would use a round-robin polling algorithm, where each STA is polled sequentially in the order in which it is placed in the polling list, although the 802.11 standard does not actually mandate the polling schedule. Priority-based polling mechanisms can also be used if different QoS levels are requested by different polled STAs. STAs which are repeatedly idle are removed from the poll cycle after several idle periods and polled again at the beginning of the next CFP.

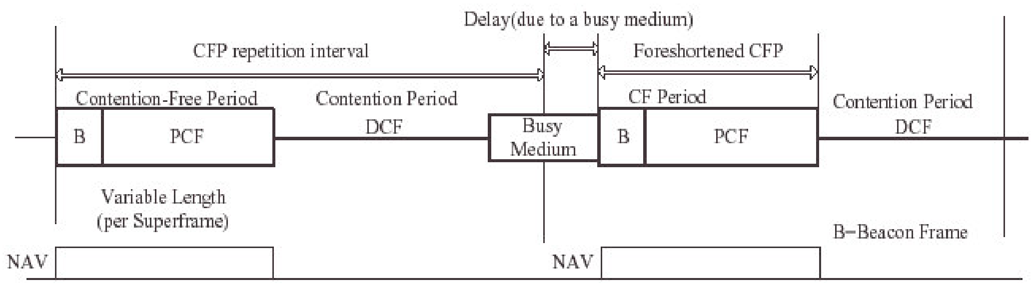

Figure 2.6 PCF and DCF Cycles

2.2 QoS Limitations of the 802.11 MAC

The wireless medium has fundamentally different characteristics from a wired medium and previous research work shows that what works well in a wired network cannot be directly applied in a wireless network. Indeed QoS issues in wired Ethernet (e.g. 802.3) have been neglected due to the relative ease with which the physical layer bandwidth has improved (1Gbit/s is now a common link speed between switches in enterprise LANs). On the other hand wireless networks have a limited capacity, (i.e. 11 Mbit/s in the case of Wi-Fi networks) owing to the limited amount of frequency spectrum available. At any given time there may be a large number of users contending for access which results in the bandwidth available to each user being severely limited.

While DCF may provide satisfactory performance in delivering best-effort traffic, it does not have any provision to support QoS, i.e. all data traffic is treated in a best-effort manner. Typically, time-bounded services such as VoIP and video streaming require stringent bandwidth, delay and jitter bounds, but are more tolerant of packet loss. Moreover in DCF, all STAs contend for the wireless medium with the same priority. So there is no differentiation between traffic types to support traffic with QoS requirements and therefore all traffic, regardless of its importance or priority, experiences the same QoS.

Although PCF has been designed to support time-bounded traffic, this mode presents many problems which leads to poor QoS performance:

- The inefficient and complex central polling scheme of PCF deteriorates the performance of high-priority traffic when the traffic load increases.
- The incompatible cooperation between CP and CFP modes leads to unpredictable delays in beacon resulting in significantly shortened CFP.
- The unknown transmission duration of a polled STA makes it difficult for the PC to predict and control the polling schedule for the remainder of the CFP.

These QoS issues for both DCF and PCF have led to a large amount of research work focussing mainly on QoS enhancement schemes for the 802.11 MAC mechanism [2][3][4][5][6]. At the same time Task Group E of the IEEE 802.11 working group has been developing an extension to the IEEE 802.11 standard, known as IEEE 802.11e [7], that proposes to make changes to the MAC mechanism to support applications with QoS requirements. The 802.11e standard is currently undergoing final revisions by the IEEE for approval sometime in 2004. It introduces the concept of Hybrid Coordination Function (HCF) for the MAC mechanism. HCF is backward compatible with DCF and PCF and at the same time it provides QoS STAs with prioritized DiffServ and parameterized IntServ QoS access to the wireless medium. HCF has two modes of operation: Enhanced Distributed Channel Access (EDCA) which is a contention-based channel access function and HCF Controlled Channel Access (HCCA) based on a polling mechanism which is controlled by the Hybrid Coordinator (HC).

2.3 IEEE 802.11e QoS Standard

The IEEE 802.11e QoS facility provides MAC enhancements to the original 802.11 MAC so as to support applications with QoS requirements. The QoS enhancements are available to QoS STAs (QSTAs) associated with a QoS AP (QAP) in a QoS BSS (QBSS). Because a QSTA implements a superset of STA functionality as defined in the 1999 edition of IEEE 802.11, the QSTA may associate with a non-QoS AP (nQAP) in a non-QoS BSS (nQBSS), to provide non-QoS MAC data service in cases where there is no QBSS to associate with. The enhancements distinguish QSTAs from non-QoS STAs (nQSTAs) and QAPs from nQAPs. These features are collectively termed "QoS facility".

There are two main functional blocks defined in 802.11e. These are the channel access functions (i.e. EDCA and HCCA) and Traffic Specification (TSPEC) management. TSPEC management provides the link between the Channel Access Functions and higher layer QoS protocols such as IntServ or DiffServ. A traffic specification describes the QoS characteristics (i.e. data rate, packet size, delay and service interval) of a Traffic Stream (TS) (i.e. a set of MSDUs to be delivered subject to a set of QoS parameters) created by negotiation between a non-AP QSTA and an HC.

2.3.1 MAC Architecture

The MAC architecture can be described as providing PCF and HCF through the services of the DCF.

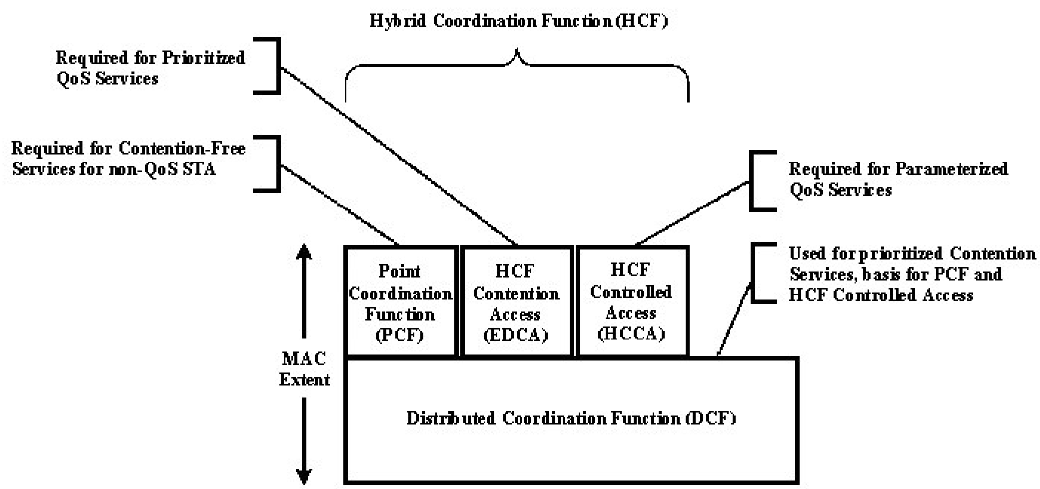

Figure 2.7 MAC Architecture

2.3.2 Hybrid Coordination Function (HCF)

The QoS facility includes an additional coordination function called HCF that is used to support parameterized IntServ QoS services. The HCF shall be implemented in all QSTAs. The HCF uses both a contention-based channel access function, called the Enhanced Distributed Channel Access (EDCA) mechanism for contention-based access and HCF Controlled Channel Access (HCCA) based on a polling mechanism for contention-free access. HCF combines and enhances aspects of the contention-based and contention-free access methods to provide QSTAs with prioritized DiffServ and parameterized IntServ QoS access to the wireless medium, while continuing to support nQSTAs for best-effort data transfer. The HCF is compatible with DCF and may also optionally contain PCF.

The basic concept of these channel access functions is the Transmission Opportunity (TXOP). A TXOP is an interval of time when a particular QSTA has the right to initiate a frame exchange sequence on the wireless medium. A TXOP is defined by a starting time and a maximum duration. QSTAs may obtain TXOPs using one or both of the channel access mechanisms. If a TXOP is obtained using the contention-based channel access, it is called an EDCA-TXOP. If a TXOP is obtained using the controlled channel access, it is called a polled TXOP.

EDCA is used only during CP, while HCCA can theoretically operate during both CFP and CP.

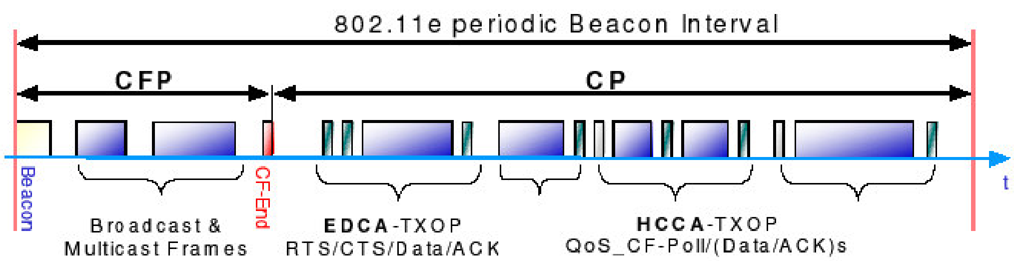

Figure 2.8 Relationship between Channel Access Mechanisms

The original standard mandated ACKs for successfully received frames. In 802.11e MAC-level ACK has become optional. This means when the "No ACK" policy is used, the MAC would not send an ACK when it has correctly received a frame. This also means the reliability of "No ACK" traffic is reduced, but it improves the overall MAC efficiency for time-sensitive traffic, such as VoIP. The "No ACK" option also introduces more stringent real-time constraints because if an ACK is not expected, then the next frame for transmission has to be ready within SIFS time from the end of the last transmission.

2.3.3 HCF Contention-based Channel Access (EDCA)

EDCA enhances aspects of the original DCF contention-based methods to provide QSTAs with prioritized QoS access to the wireless medium for 8 priorities. EDCA channel access defines the Access Category (AC) mechanism that provides support for the priorities at the QSTAs. Each QSTA may have up to 4 ACs to support 8 User Priorities (UPs). One or more UPs are assigned to one AC. A QSTA accesses the medium based on the access category of the frame that is to be transmitted. The mapping from priorities to access categories is defined in the following table.

Priority	User priority (UP – Same as 802.1D User Priority)	Access Category (AC)	Designation (Informative)
Lowest	1	0	Background
	2	0	Background
	0	1	Best Effort
	3	2	Video
	4	2	Video
	5	2	Video
	6	3	Voice
Highest	7	3	Voice

Table 2.1 User Priority to Access Category Mappings

Each AC has its own transmit queue and its own set of EDCA parameters used by the channel access function to control its operation. The differentiation in priority between ACs is realised by setting different values of EDCA parameters:

- EDCA uses the Contention Window (CW) size to change the priority of each AC. Indeed the CW limits (CW_{min} and CW_{max}) from which the random backoff is computed are not fixed as with DCF, but are instead variable. Assigning a small CW_{min} and CW_{max} to a high AC ensures that in most cases, the high-priority AC will be able to transmit ahead of low-priority ACs.

- For further differentiation the minimum specified idle duration time before trying to access the medium or starting to decrement the backoff timer is not the constant value DIFS as defined for DCF, but is instead a distinct value called Arbitration Inter Frame Spacing (AIFS) which equals a DIFS plus a number of time slots (which may be zero). This means that an AC using a large AIFS (i.e. many extra time slots) will have lower priority than an AC using a small AIFS, since they will have to wait longer on average before trying to access the medium or starting to decrement the backoff timer.

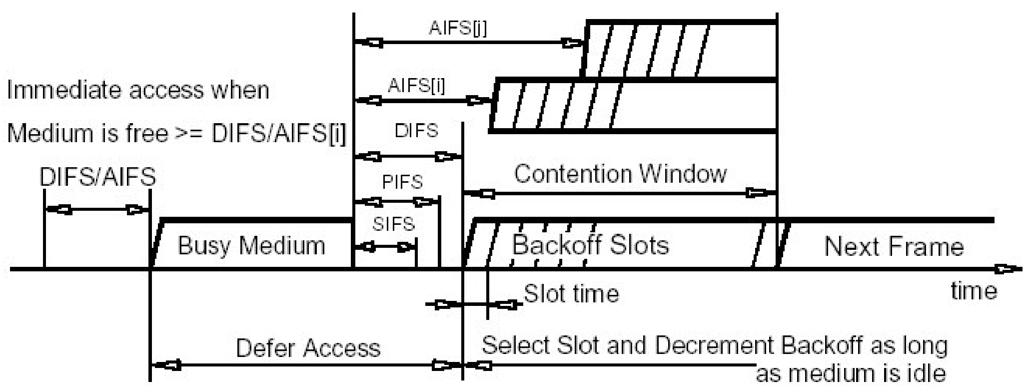

Figure 2.9 IFS Relationships of IEEE 802.11e

When a new MSDU (MAC Service Data Unit) arrives at the MAC, EDCA first classifies it with the appropriate AC (i.e. the UP value associated with the MSDU is mapped onto an AC) and then buffers it into the appropriate AC transmit queue. Then MSDUs from different ACs contend for EDCA-TXOP internally within the QSTA. Collisions between contending MSDUs within a QSTA are resolved within the QSTA such that the MSDU from the high-priority AC receives the TXOP and the MSDU from the lower-priority colliding ACs behave as if there was an external collision on the wireless medium. However, this collision behaviour does not include setting retry bits in the MAC headers of MPDUs, as this would be done after a transmission attempt that was unsuccessful due to an actual external collision on the wireless medium.

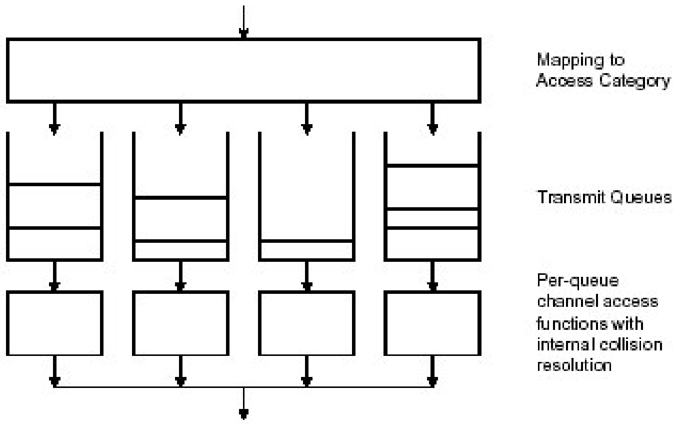

Figure 2.10 EDCA Implementation Model

The winning AC would then contend externally for the wireless medium.

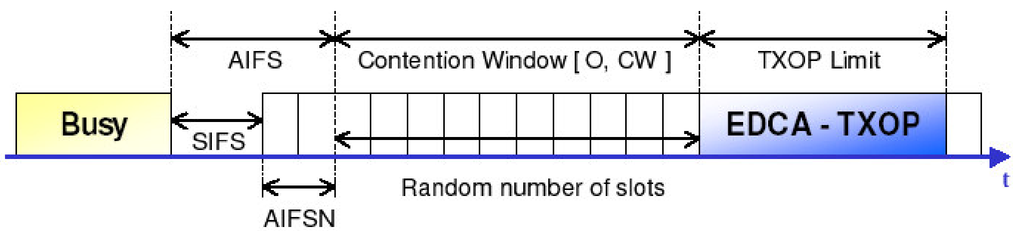

Figure 2.11 Example Implementation of the External Contention

AIFS is a duration derived from the Arbitration Inter Frame Spacing Number (AIFSN) by the relation:

$$AIFS = AIFSN \times Slot\ Time + SIFS \qquad \text{(equation 2.2)}$$

AIFSN indicates the number of slots times following a SIFS duration a QSTA should defer before either invoking a backoff or starting a transmission. The minimum value for AIFSN is 2.

During an EDCA-TXOP won by an AC, a QSTA may initiate multiple frame exchange sequences (i.e. packet bursting) to enhance the performance and achieve better medium utilization. The QSTA is allowed to send as many frames it wishes as long as the total access time (i.e. EDCA-TXOP) does not exceed the value of the TXOP limit parameter. A value of 0 means that the EDCA-TXOP is limited to a single MSDU. To ensure that no other QSTA interrupts the packet burst, the interframe space used between the reception of an ACK and the transmission of the next data frame is a SIFS. If a collision occurs (no ACK frame is received), the packet burst is terminated. Since packet bursting might increase the jitter, it is recommended that TXOP Limit is chosen such that it is not longer than the time required for the transmission of a data frame of maximum size.

With proper tuning of AC parameters, traffic performance from different ACs can be optimized as well as achieving prioritization of traffic. This requires a central coordinator QAP to maintain a common set of AC parameters to guarantee fairness of access for all QSTAs within the QBSS. This is further enhanced by an admission control mechanism which would protect the performance of existing traffic.

2.3.4 HCF Controlled Channel Access (HCCA)

The HCCA mechanism uses a QoS-aware centralized coordinator, called a Hybrid Coordinator (HC) and operates under rules that are different from the Point Coordinator (PC) of the PCF. The HC is collocated with the QAP of the QBSS and uses the HCs higher priority of access to the wireless medium to initiate frame exchange sequences and to allocate TXOPs to itself and other QSTAs so as to provide limited duration Controlled Access Phase (CAP) for contention-free transfer of QoS data.

HC traffic delivery and TXOP allocation may be scheduled during both the CFP and CP, to meet the QoS requirements of particular Traffic Stream (TS). TXOP allocations and contention-free transfers of QoS traffic can be based on the HC's QBSS-wide knowledge of the amounts of pending traffic belonging to different TS and subject to QBSS-specific QoS policies.

Controlled Access Phases (CAPs) are defined as several intervals within one CP when short bursts of frames are transmitted using polling-based controlled channel access mechanisms. During the remainder of the CP, all frames are transmitted using the EDCA contention-based rules. The following figure shows the relationship of CFP, CP and CAPs. CAPs may also include Controlled Contention Intervals (CCIs), during which contention occurs only when QSTAs need to request new TXOPs.

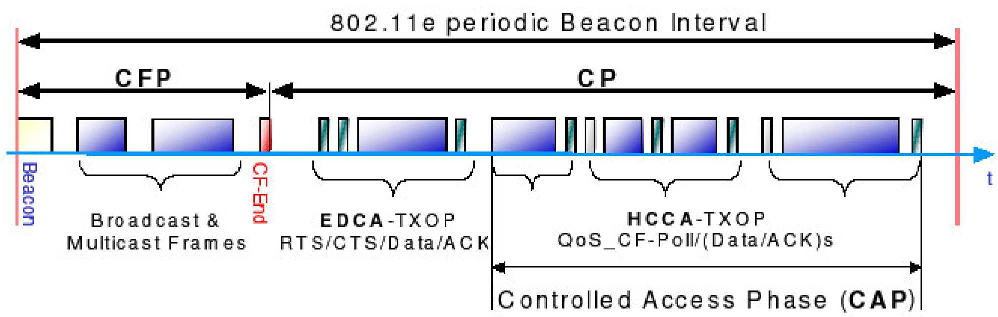

Figure 2.12 Relationship between CFP, CP and CAP

A QAP may indicate availability of CF-Polls to nQSTAs, thereby providing non-QoS contention-free transfers during the CFP. However the 802.11e standard does not recommend using HCCA during CFP. This is mainly due to the complexity involved in implementing polling using CF-Poll and QoS CF-Poll at the same time.

2.4 QoS Metrics

In order to measure the level of QoS experienced by a QSTA, there are a number of important QoS performance metrics associated with time-bounded traffic that need to be monitored such as throughput, delay, jitter (delay variation) and packet loss.

- Throughput: This is a measure of the amount of data that will be sent across a network per unit of time. This is usually measured in bits per second (or packets per second).

- Delay: This is also known as latency and is defined as the period of time it takes for a transmitted packet to get from its source to its destination.

- Jitter: This is also known as delay variation and is defined as the variation in inter-packet arrival time (at the receiver) introduced by the variable transmission delay over the network. Jitter can be minimised by introducing a jitter buffer to remove this variation, however the buffer causes additional delay which adds to the overall delay.

- Packet loss: This is a measure of the maximum acceptable packet loss that can be tolerated by voice and video while still maintaining a good level of quality. This is normally a percentage of the overall packet transmission.

The following table shows QoS performance requirements for time-bounded applications [9]:

Application	**Throughput requirements**	**Key performance parameters and requirements**		
		One-way delay	Jitter	Packet Loss Rate (PLR)
VoIP	4-64 kbit/s	<150 ms preferred <400 ms limit	<40-50 ms	<3 %
Video Conferencing	16-384 kbit/s	<150 ms preferred <400 ms limit	<40-50 ms	<1%
Video Streaming	16-384 kbit/s	<10 sec		<1%

Table 2.2 QoS Performance Metrics for Time-bounded Applications

VoIP:

- Heavily influenced by one-way delay which may result in echo and impacts on conversational dynamics.
- Intolerant to jitter.
- Human ear is tolerant to a certain amount of information loss.

Video Conferencing:

- Requires a full-duplex system, carrying both voice and video and intended for use in a conversational environment.
- Same delay and jitter requirements as for conversational voice (i.e. VoIP).
- Human eye is tolerant to a certain amount of information loss
- Added requirements that the audio and video must be synchronised within certain limits to provide "lip-synch" (lip-synch < 80 ms) [9].

Video streaming:

- No conversational element involved, meaning that the delay requirements will be less stringent.

2.5 Computer Simulator

As the IEEE 802.11e enhanced QoS standard is not yet ratified and no equipment supporting the standard is yet available, performance studies on 802.11e can only be based upon simulation. Consequently in order to evaluate the performance of the 802.11e MAC mechanism, an existing 802.11b DCF MAC protocol computer simulation model previously developed in the context of the WITM research project at the Dublin Institute of Technology [10] was extended to include queuing and prioritisation-scheduling mechanisms in order to realise an 802.11e simulator. The simulator has been implemented while referring to the specification of the latest draft of the 802.11e standard [7]. The simulator was developed in C/C++ and essentially implements the 802.11e MAC mechanism. Of the various features defined in the latest draft, there are some that we did not implement in the MAC for simplicity, i.e. the HCCA polling mechanism for contention-free channel access. We simulated the contention-based channel access EDCA mechanism and did not consider other features such as EDCA-TXOP and the "No ACK" policy in the simulation. Any STA gaining access to the medium transmits one packet and then releases the channel for the next STA. We consider a BSS infrastructure-type WLAN, hence all the traffic within the WLAN is handled by a single AP, i.e. no direct links or ad-hoc operation have been simulated.

The simulator implements FIFO buffers in every QSTA and is able to gather detailed statistics information about the MAC Buffer, e.g. it records the position in the queue where packets are buffered, queue lengths, buffer overflow, etc. The simulator also collects statistical information on the MAC mechanism, e.g. it records the number of transmission attempts it took to successfully transmit a packet or if it was dropped.

The simulator calculates local QoS metrics (i.e. throughput, delay, jitter and packet loss) for each QSTA from a simulation run in order to monitor the level of QoS experienced by the QSTAs.

2.6 Background Material

The IEEE 802.11e standard is an emerging technology and therefore there are few direct references to it. However, the issue of QoS provisioning in both wired and wireless networks is in general a well-researched area. Consequently a large number of publications in this area have been consulted as background material in carrying out this study.

A list of this background material has been included after the Bibliography at the end of the thesis.

Chapter 3

Quality of Service and 802.11

3.1 State of the Art

Previous research into the performance evaluation of 802.11 has been carried out by using computer simulations or by means of analytical models.

In order to support QoS in the 802.11 MAC, many QoS enhancement schemes have been proposed by several research workers. In this section we first outline some of these schemes and then we review a number of the major contributions to the field.

3.1.1 QoS Enhancement Schemes Overview

AC scheme: To introduce priorities in IEEE 802.11 using DCF, *Aad* and *Castellucia* [2] propose three techniques. Each technique uses different parameters to provide service differentiation. Henceforth we shall refer to it as the AC scheme.

- Different backoff increase function (also called the scaling contention window scheme) where each priority level has a different backoff increment function. Assigning a short contention window to the higher priority STAs ensures that in most cases, high-priority STAs are more likely to access the channel than low-priority ones. This method modifies the CW of the priority level j after i transmission attempts as follows:

$$CW_{new} = P_j^{\ 2+i} \times CW_{old} \qquad \text{(equation 3.1)}$$

where P_j is a factor used to achieve service differentiation which has a higher value for lower priority STAs. Experiments show that this scheme performs well with UDP (User Datagram Protocol) traffic but not so well with TCP (Transmission Control Protocol) traffic because TCP ACKs affect the differentiation mechanism since all ACKs have the same priorities.

- Different DIFS: Each STA has a different DIFS according to its priority level. For example, $DIFS_{j+1} < DIFS_j < DIFS_{j-1}$. So before transmitting a packet, the STAs having priority $j+1$ will wait for an idle period of length $DIFS_{j+1}$ slot time which is shorter than that of STA with priority j. To avoid collision between frames of the same priority, the backoff mechanism is maintained in a way that the maximum contention window size added to $DIFS_j$ is $DIFS_{j-1}$ - $DIFS_j$. This ensures that no STA of priority $j+1$ has queued frames when a STA of priority j starts transmission. The main issue of this scheme is that low priority traffic suffers as long as high priority frames are queued. Moreover TCP ACKs also reduce the effects of service differentiation since all ACKs have the same priorities.

- Different maximum frame length: Each STA has a different maximum frame length according to its priority level. Here there are two possibilities: One is either to drop packets that exceed the maximum frame length assigned to a given STA (or simply configure it to limit its packet lengths), the other is to fragment packets that exceed the maximum frame length. This mechanism is used to increase both transmission reliability and differentiation and works well for TCP and UDP flows. However, in a noisy environment long packets are more likely to be corrupted than short ones which decreases the differentiation efficiency of this scheme.

DENG scheme: *Deng* and *Chang* [3] have proposed a service differentiation scheme that requires minimal modifications to the IEEE 802.11 DCF MAC protocol. Henceforth we will refer to it as the Deng scheme.

The Deng scheme uses two properties of IEEE 802.11 to provide differentiation: The Inter Frame Space (IFS) used between data frames and the backoff mechanism. If two STAs use a different IFS, the STA with the shorter IFS will get higher priority than a STA with a longer IFS. Since the IEEE 802.11 standard already defines two kinds of IFS (PIFS and DIFS) to assure that no low priority traffic is sent during the contention-free period of the PCF, these can be used for easy implementation of the Deng scheme. By using these two different interframe spaces, traffic can be differentiated in terms of two classes. To further extend the number of available classes, the backoff mechanism could be used to differentiate between STAs. This is done by designing the backoff algorithm such that it generates backoff intervals at different times, depending on the priority of the STA. Therefore four classes of priorities can be supported using two different interframe spaces and two different backoff algorithms. The backoff algorithm chosen guarantees that STAs that use the low-priority backoff algorithm always generate longer backoff intervals than STAs with higher priority.

DFS scheme: *Vaidya* and *Bahl* [4] have proposed an access scheme which utilizes the ideas behind fair queuing in the wireless domain. This access scheme is called the Distributed Fair Scheduling (DFS) algorithm. In this context, fair means that each flow gets bandwidth proportional to some weight that has been assigned to it. Since different weights can be assigned to the flows, this can be used for differentiation between flows.

The DFS scheme is based on the fair queuing mechanism known as Self-Clocked Fair Queuing (SCFQ) and uses the backoff mechanism of IEEE 802.11 to determine which STA should send first. Before transmitting a frame, the backoff process is always initiated, even if no previous frame has been transmitted. The backoff interval calculated is proportional to the size of the packet to send and inversely proportional to the weight of the flow. This causes STAs with low weights to generate longer backoff intervals than those with high weights, thus getting lower priority. Fairness is achieved by including the packet size in the calculation of the backoff interval, causing flows with smaller packets to get to send more often. This gives flows with equal weights the same bandwidth regardless of the packet sizes used. If a collision occurs, a new backoff interval is calculated using the backoff algorithm of the IEEE 802.11 standard.

Blackburst scheme: *Sobrinho* and *Krishnakumar* [5] have proposed a scheme called Blackburst where the main goal is to minimise the delay for real-time traffic. Blackburst requires that all high priority STAs try to access the medium with equal and constant intervals, t_{sch} and have the ability to jam the medium for a period of time.

When a high priority STA wants to send a frame, it senses the medium to see if it has been idle for PIFS and then sends its frame. If the medium is busy, the STA waits for the medium to be idle for a PIFS and then enters a Blackburst contention period. The STA sends a so-called "Blackburst" to jam the channel. The length of the Blackburst is determined by the time the STA has waited to access the medium and is calculated as a number of black slots. After transmitting the Blackburst, the STA listens to the medium for a short period of time (less than a black slot) to see if some other STA is sending a longer Blackburst which would imply that the other STA has waited longer and thus should access the medium first. If the medium is idle the STA will send its frame, otherwise it will wait until the medium becomes idle again and enters another Blackburst contention period. By using slotted time and imposing a minimum frame size on real time frames, it can be guaranteed that each Blackburst contention period will yield a unique winner.

After the successful transmission of a frame, the STA schedules the next transmission attempt t_{sch} seconds in the future. This has the benefit that real-time flows will synchronize and share the medium in a TDMA (Time Division Multiple Access) fashion. In the Blackburst scheme, low priority STAs use the ordinary CSMA/CA access method of IEEE 802.11. This means that unless some low priority traffic comes and disturbs the order, few Blackburst contention periods will have to be initiated once the STAs have synchronized. The main drawback of Blackburst is that it requires constant access intervals for high-priority traffic otherwise the performance degrades considerably.

AEDCF scheme: In order to efficiently support time-bounded multimedia applications, *Romdhani* and *Turletti* [6] have proposed a scheme called Adaptive Enhanced Distributed Coordination Function (AEDCF) that uses a dynamic procedure to change the CW value after each successful transmission or collision. After each successful transmission, the EDCA mechanism resets the contention window $CW[i]$ of the corresponding class i to $CW_{min}[i]$ regardless of the network conditions. Instead the AEDCF scheme proposes to reset the $CW[i]$ values more slowly to adaptive values (different to $CW_{min}[i]$) taking into account their current sizes and the average collision rate while maintaining the priority-based discrimination.

The simplest scheme that can be used to update the $CW[i]$ of each class i is to reduce it by a static factor such as $0.5 \times CW_{old}$. However, a static factor cannot be optimal in all network conditions. The AEDCF scheme proposes that every class updates its CW in an adaptive way taking into account the estimated collision rate f^{j}_{curr} in each STA. Indeed, the collision rate can give an indication about contentions in a distributed network. The value of f^{j}_{curr} is calculated using the number of collisions and the total number of packets sent during a constant period (i.e. a fixed number of slot times).

To minimize the bias against transient collisions, an estimator of Exponentially Weighted Moving Average (EWMA) is used to smooth over the estimated values. Let f^{j}_{avg} be the average collision rate at step j (for each update period) computed according to the following iterative relationship:

$$f^{j}_{avg} = (1 - \alpha) \times f^{j}_{curr} + \alpha \times f^{j-1}_{avg} \qquad \text{(equation 3.2)}$$

where j refers to the j^{th} update period, f^{j}_{curr} stands for the instantaneous collision rate and α is the weight (also called the smoothing factor).

To ensure that the priority relationship between different classes is still fulfilled when a class updates its CW, each class should use a different factor according to its priority level, this factor is called the Multiplication Factor (MF). Keeping in mind that the factor used to reset the CW should not exceed the previous CW, the maximum value of MF is limited to 0.8. This limit has been fixed according to an extensive set of simulations calculated with several scenarios. The MF of class i is defined as follows:

$$MF[i] = min\{(1 + (i \times 2) \times f^{j}_{avg}, 0.8)\} \quad \text{(equation 3.3)}$$

This formula allows the highest priority class to reset the CW parameter with the smallest MF value.

After each successful transmission of packet of class i, $CW[i]$ is then updated as follows:

$$CW_{new}[i] = max\{(CW_{min}[i], CW_{old}[i] \times MF[i])\} \quad \text{(equation 3.4)}$$

This equation guarantees that $CW[i]$ is always greater than or equal to $CW_{min}[i]$ and that the priority access to the wireless medium is always maintained.

In the current version of EDCA, after each unsuccessful transmission of a packet of class i, the CW of this class is doubled, while remaining less than the maximum contention window $CW_{max}[i]$. In AEDCF, after each unsuccessful transmission of packet of class i, the new CW of this class is increased with a Persistence Factor $PF[i]$ which is set differently for different priority classes, yielding high priority classes with a smaller value of $PF[i]$:

$$CW_{new}[i] = min\{(CW_{max}[i], CW_{old} \times PF[i])\} \quad \text{(equation 3.5)}$$

This mechanism offers high priority traffic a higher probability of generating a smaller CW value than low priority traffic. This PF parameter has been proposed in previous versions of the 802.11e draft but has since been removed. The AEDCF scheme re-introduces it because it can reduce the probability of a new collision and consequently decrease delay.

3.1.2 Literature Overview

In [11] *Lindgren* and *Almquist* evaluate four mechanisms for providing service differentiation in IEEE 802.11 wireless LANs. The evaluated schemes are the Point Coordinator Function (PCF) of IEEE 802.11, the Enhanced Distributed Channel Access (EDCA) of the proposed IEEE 802.11e extension to IEEE 802.11, Distributed Fair Scheduling (DFS) and Blackburst. The evaluation was done using the Berkeley *ns*-2 network simulator. Furthermore, the impact of some parameter settings on performance has also been investigated. The metrics used in the evaluation are throughput, medium utilisation, collision rate, average access delay and delay distribution for a variable load of real-time and background traffic. The simulations show that the best performance is achieved by Blackburst. PCF and EDCA are also able to provide pretty good service differentiation. DFS can give a relative differentiation and consequently avoids starvation of low priority traffic. Evaluation includes both some trade offs in parameter settings for individual schemes and performance comparisons between the different schemes.

The simulations show that when using PCF, it is important to select a proper size for the superframe which determines how often poll frames are sent to high priority STAs. To obtain good performance for high priority traffic without wasting resources on unnecessary control frames, the superframe should be approximately as long as the interval between packets generated by a high priority STA.

When comparing the schemes, the simulations show that Blackburst gives the best performance of the evaluated schemes to high priority traffic both with regard to throughput and access delay. At low loads, it also gives acceptable performance to low priority traffic, but it does however deteriorate to complete starvation of low priority traffic at high loads. A drawback with Blackburst is the requirement for constant access intervals that it imposes on high priority traffic. If these cannot be met, EDCA might be a suitable alternative. Although not being able to provide as good a service as Blackburst and also suffering from a high rate of collisions, it can still serve many high priority STAs and give low delay to high priority traffic.

Both Blackburst and EDCA starve low priority traffic when there is high loads of high priority traffic which in many cases is not desirable. If relative differentiation is desired, DFS would be better. It ensures better service to high priority traffic and still does not starve low priority traffic (ensuring that it gets its fair share of the bandwidth).

Further, the simulations show that the Blackburst scheme gives the best medium utilization at reasonable loads of high priority traffic. This is important given the scarcity of bandwidth in wireless networks. This paper shows that Blackburst is good at avoiding collisions between high priority STAs, while EDCA suffers from a high rate of collisions.

Contrary to EDCA and DFS, Blackburst and PCF transmit bursts and control frames on the channel to determine which STA should get access to the medium. During those transmissions, the channel is occupied and cannot be used for any useful transmission of data. It is shown that for Blackburst, this overhead is rather low up to a certain point of high priority load, after which the amount of overhead increases rapidly. For PCF, the overhead is quite large and increases with the number of high priority STAs.

Finally, the paper concludes with the observation that it is difficult to say that any one QoS scheme is better than another, since it largely depends on the context in which it is to be used and which results are desired. It can be said that Blackburst works well in many scenarios, but scenarios certainly exist where some of the other schemes would be preferable. Before deciding on what QoS scheme to use in a network, an analysis of what the network should be used for and what kind of services are required to be supported.

In [6] *Romdhani* and *Turletti* describe an adaptive service differentiation scheme for QoS enhancement in IEEE 802.11 wireless ad-hoc networks. This approach is called Adaptive Enhanced Distributed Coordination Function (AEDCF) and is derived from the new EDCA to be introduced in the upcoming IEEE 802.11e standard. This scheme aims to share the transmission channel efficiently. Relative priorities are provisioned by adjusting the size of the CW of each traffic class taking into account both application requirements and network conditions. This paper evaluates through simulations the performance of AEDCF and compares it with the EDCA scheme proposed in the 802.11e. The evaluation was done using the Berkeley *ns*-2 network simulator. The metrics used in the evaluation are gain of throughput, mean delay, latency distribution, medium utilization and collision rate.

The main outcome in this paper is the design of a new adaptive scheme for QoS enhancement for IEEE 802.11 WLANs. The 802.11e EDCA scheme is extended by dynamically varying the contention window of each active class of service. Results show that AEDCF outperforms the basic EDCA, especially at high traffic load conditions. Indeed, the scheme increases the medium utilization ratio and reduces the collision rate by more than 50%. While achieving delay differentiation, the overall throughput obtained is up to 25% higher than EDCA. Moreover, the complexity of AEDCF remains similar to the EDCA scheme, enabling the design of cheap implementations. The results were validated by analyzing the impact of sources and network dynamics on the performance metrics and comparing the results obtained with EDCA and the static slow decrease schemes.

Although AEDCF is intended to improve performance of wireless ad-hoc networks, the same idea can be used in the infrastructure mode with some changes. Future work could include adapting other parameters such as CW_{max}, the maximum number of retransmissions and the packet burst length according to the network load rate.

In [12] *Li* and *Battiti* aim at gaining an insight into three mechanisms to differentiate among traffic categories, i.e. differentiating the minimum CW size (CW_{min}), IFS and the length of the packet payload according to the priority of different traffic categories. This paper proposes an analytical model to compute the throughput and packet transmission delays in a WLAN with enhanced IEEE 802.11 DCF which supports service differentiation. In the analytical model, service differentiation is supported by scaling CW, IFS and the packet length according to the priority of each traffic flow. Comparisons with simulation results show accurate performance evaluations can be achieved by using the proposed model.

This paper concludes that:

1. The settings of CW_{min} for different types of traffic flows have a significant influence on the throughput and packet delay. One type of traffic gains priority over other types of traffic through a smaller CW_{min}. More channel resources are occupied, with a smaller packet delay.

2. Traffic flows with a shorter IFS obtain higher priority to access the channel resources. However, excessive IFS values cause long packet delays for traffic flows with lower priority, bordering on starvation.

3. The length of packet payload for different types of traffic directly influences the bandwidth allocation among different traffic flows. However, the differentiation of packet payload size has little influence on the differentiation of packet delays. This paper notes that in noisy channel conditions, the typical situation in wireless LANs, longer payloads suffer a higher error probability and this fact may discourage applying payload length variability as a differentiation mechanism.

4. The number of traffic flows with higher priority must be limited to maintain the system working at a high performance regime by suitable access control or pricing schemes.

5. By adopting the scheme of scaling CW_{min} and packet payloads, approximate and simple relationships exist between throughput, packet delays and lengths of packet payload of different traffic types. These relationships can be used for the optimal design of the whole system.

By using the proposed model, three different service differentiation schemes have been analyzed. The schemes are not mutually exclusive. The appropriate choice and setting of parameters for the control of a real-world system, including access control, is an interesting area of future research that can benefit from the analysis presented in this paper.

3.2 Computer Simulator Overview

In order to gain a deeper insight into the proposed IEEE 802.11e QoS enhanced standard with service differentiation support, system modelling and performance analysis are needed. We propose a computer simulation model that faithfully implements the latest draft of the 802.11e standard [7]. The simulator was developed in C/C++ and essentially implements the 802.11e MAC mechanism. We simulated the contention-based channel access EDCA mechanism only and have implemented FIFO buffers in every STA which allowed us to calculate throughput, packet delay, jitter and packet loss which are important QoS metrics when measuring and monitoring the level of QoS experienced by STAs. The simulator was tested using performance results from published papers on the 802.11e standard to ensure correct implementation of the standard by the simulator. After being completely satisfied with the correct operation of the simulator, traffic-engineering tests were carried out with regard to throughput and packet loss. The objective here was to identify the effects of varying the 802.11e parameters on performance. From the range of tuneable parameters that 802.11e offers, we have identified the two most important parameters for QoS provisioning, namely AIFS which is the minimum time interval between the wireless medium becoming idle and the start of transmission of a frame and the CW size from which a random number is drawn as part of the access mechanism. As a result of these tests a good understanding of the effects of these two parameters on performance was achieved. We have identified that it is possible to allocate bandwidth for a STA by the appropriate setting of the 802.11e parameters and thereby improve QoS support for STAs or classes of service in IEEE 802.11 networks. EDCA provides significant improvements for high priority QoS traffic, however these improvements are typically achieved at the cost of reduced performance for lower priority traffic. Despite these problems, we find that EDCA is attractive because of its simplicity and its ability to provide QoS differentiation which is an important improvement over legacy DCF.

3.3 MAC Bandwidth Components

In order to gain an insight into the operation of the 802.11e MAC mechanism we have identified a set of MAC bandwidth components that present a useful and intuitive descriptive framework of the MAC mechanism. At any given time the wireless medium can be either busy (STAs are transmitting frames) or idle (the wireless medium is not in use). Based on this observation we define the MAC bandwidth components that describe the MAC operation. First, the load bandwidth (BW_{load}) corresponds to the bandwidth used for frame transmission and which determines the throughput of a STA. Next, the idle bandwidth (BW_{idle}) corresponds to the unused bandwidth on the wireless medium (i.e. when no frames are being transmitted). The BW_{idle} subdivided into two components: The access bandwidth (BW_{access}) which corresponds to the idle bandwidth required by STAs when accessing the medium prior to starting frame transmission and the free bandwidth (BW_{free}) which corresponds to the remaining unused idle bandwidth.

The following figure shows the different time components associated with these MAC bandwidth components in the wireless medium.

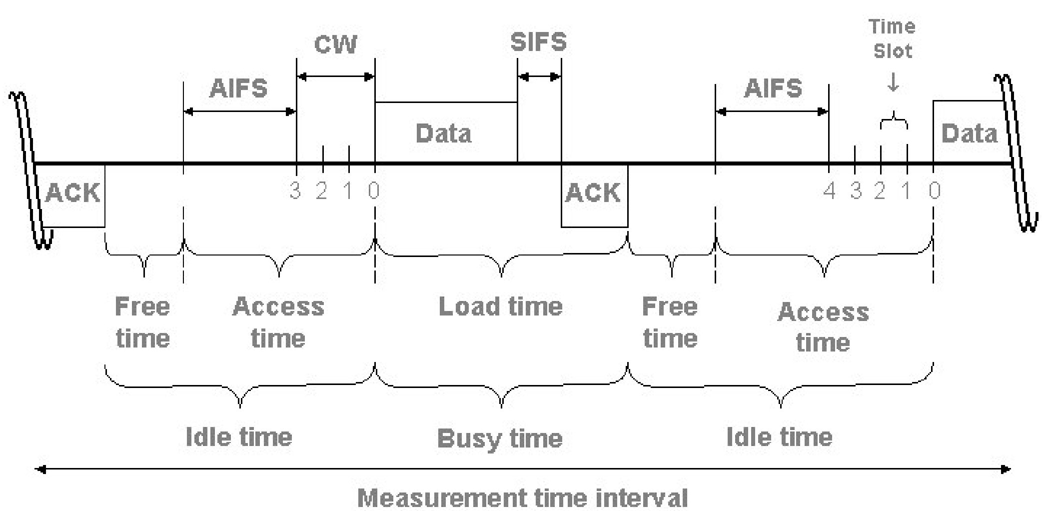

Figure 3.1 Time Components for the MAC Mechanism

Summing the STAs' load time $T^{(i)}_{load}$ components over the measurement time interval of interest gives the medium busy time:

$$T_{busy} = \sum_{i=1}^{n} T^{(i)}_{load} \qquad \text{(equation 3.6)}$$

The medium idle time contains two time components, i.e. an access $T^{(i)}_{access}$ and a free time $T^{(i)}_{free}$:

$$T_{idle} = T^{(i)}_{access} + T^{(i)}_{free} \quad \text{for all stations } i \qquad \text{(equation 3.7)}$$

$T^{(i)}_{access}$ depends primarily on the STA's offered load but also on the other STAs' loads. For example, a STA will have to stop decrementing its BC if another STA starts transmitting and will only resume decrementing when the wireless medium becomes idle again which ultimately will increase the STA's access time. In addition, the selection of the initial BC value is a random process which results in the entire access mechanism being inherently stochastic, i.e. $T^{(i)}_{access}$ is a random quantity.

$T^{(i)}_{free}$ arises from the idle time intervals when a STA does not have a packet awaiting transmission and will vary between STAs depending on their respective offered loads and access requirements. This free time on the medium $T^{(i)}_{free}$ can be viewed as spare capacity on the medium, essentially acting as a reservoir that can be drawn on when required. The amount of free time experienced by a STA is closely related to the level of QoS experienced by its traffic load where the greater the free capacity available to a STA, the better the QoS likely to be experienced.

The medium idle time is shared commonly by all STAs and depending on their offered loads and access requirements will make different use of it.

$$T_{idle} = T^{(1)}_{access} + T^{(1)}_{free} = \ldots = T^{(i)}_{access} + T^{(i)}_{free} = \ldots = T^{(n)}_{access} + T^{(n)}_{free} \qquad \text{(equation 3.8)}$$

For example, in the case of a STA that is saturated (i.e. there is always a packet awaiting transmission in its buffer), it will use all of the available idle time to obtain access for its load. Consequently, $T_{access}^{(i)} = T_{idle}$ and hence $T_{free}^{(i)} = 0$. Therefore, one would expect the STA to have a poor QoS. Similarly, in the case of a non-saturated STA, $T_{access}^{(i)} < T_{idle}$ and hence $T_{free}^{(i)} > 0$ resulting in a better QoS.

Equations (3.6) to (3.8) serve to illustrate how the performance of STAs are coupled under the MAC mechanism. For example, a heavily loaded STA *i* will have a large $T_{load}^{(i)}$ leading to a large value for T_{busy}. This has the effect of reducing the T_{idle} available to all STAs, leading to a reduced T_{free} and possibly T_{access} for all STAs. Consequently, the performance of all STAs can be affected by the presence of a heavily loaded STA.

The MAC bandwidth components are calculated on a per STA basis, e.g. for $BW_{free}^{(i)}$:

$$BW_{free}^{(i)} = \frac{T_{free}^{(i)}}{T_{load}^{(i)} + T_{access}^{(i)} + T_{free}^{(i)}} \times 11\,Mbit/s \qquad \text{(equation 3.9)}$$

We multiply by 11 Mbit/s to normalise to the line rate (11 Mbit/s PHY operation is assumed here).

As outlined above, the MAC bandwidth components are related according to:

$$BW_{free}^{(i)} = BW_{idle} - BW_{access}^{(i)} = 11 - \sum_{i=1}^{n} BW_{load}^{(i)} - BW_{access}^{(i)} \qquad \text{(equation 3.10)}$$

The following figure shows the performance characteristic of two wireless STAs (STA_1 and STA_2) in terms of their combined loads (BW_{load}), BW_{free} and Packet Loss Rate (PLR) as a function of STA_2's offered load when using the legacy DCF, i.e. AIFS = DIFS for both STAs. The two wireless STAs carry identical traffic types and generate packets with a packet size equal to 512 bytes and an exponentially distributed inter-arrival time, i.e. Poisson traffic. The load presented to the wireless medium by STA_1 is held fixed at 250 pps (packets per second), whereas the load presented by STA_2 is ramped from zero to full saturation in steps of 50 pps.

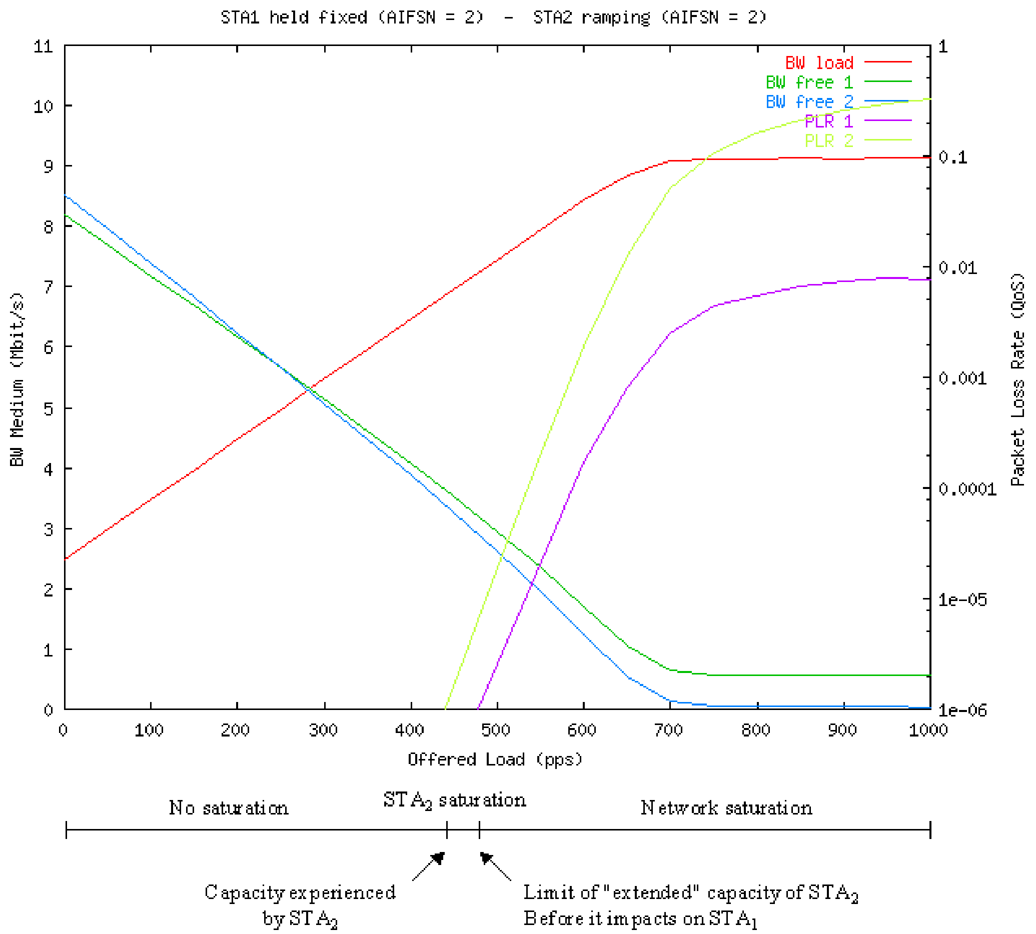

Figure 3.2 Two STAs Scenario using the Legacy DCF

It is apparent from the figure that there are quite distinct regions of saturation. When the combined BW_{load} of STA_1 and STA_2 is small, both STAs have sufficient BW_{free} and hence both STAs experience a high QoS (i.e. negligible PLR), this corresponds to the region of no saturation. As the load from STA_2 increases both STAs experience a reduced BW_{free} until a point is reached where the QoS experienced by STA_2 begins to deteriorate (i.e. the PLR for STA_2 rises dramatically). At this point STA_2 begins to saturate and the offered load here represents the capacity of the network as seen by STA_2. As the load presented by STA_2 continues to increase, quickly a point is reached where it begins to noticeably impact on the performance of STA_1, i.e. its QoS starts to deteriorate. This point represents the onset of network saturation where both STAs no longer have sufficient BW_{free} and hence both STAs experience poor QoS. The question here is to determine how much BW_{free} needs to be available in order to support QoS requirements. It is clear that STA_1 and STA_2 require different amounts of BW_{free} given that the nature of their loads are different.

In the following figure the relationship between the MAC bandwidth components and the nature of their interaction is described.

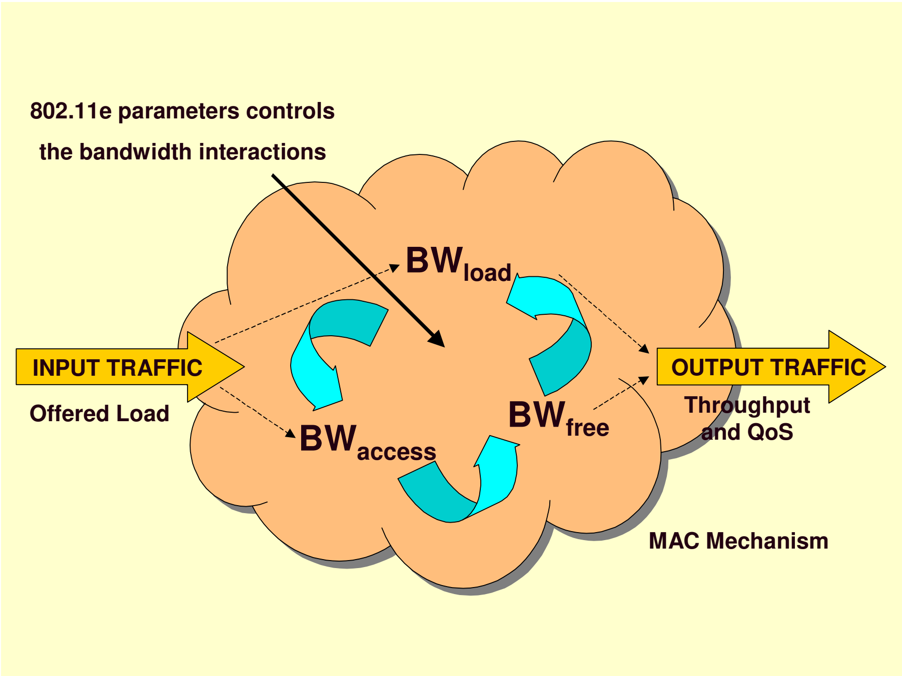

Figure 3.3 Relationship between MAC Bandwidth Components

As mentioned above the BW_{load} is used for frame transmission and determines the throughput of a STA. The BW_{idle} is the unused bandwidth on the wireless medium (i.e. when no frames are being transmitted) and subdivided into two components: The BW_{access} which is the idle bandwidth required by STAs when accessing the medium prior to starting frame transmission and the BW_{free} which is the remaining unused idle bandwidth that will determine the QoS experienced by the STAs.

As mentioned in section 3.2 we have identified the two most important 802.11e parameters, namely AIFS and the CW size that determine QoS and as a result of many tests we have achieved a good understanding of the effects these two parameters have on performance. We have identified that by varying both AIFS and the size of CW it is possible to control the interaction between the MAC bandwidth components in order to prioritise a particular STA over another and thereby improve its QoS (see chapter 5).

3.4 MAC Bandwidth Components Simulation Results

In the next chapter, an 802.11e MAC simulator developed in C/C++ will be described. The simulator explicitly calculates the MAC bandwidth components (i.e. BW_{load}, BW_{idle}, BW_{access} and BW_{free}). The simulator will be used to generate performance plots similar to Figure 3.2 for a number of different test scenarios involving a range of different traffic loads and priorities in order to assess the potential for QoS provisioning in the proposed 802.11e MAC enhancement standard.

Chapter 4

Computer Simulator

The simulator has been developed in C/C++ and essentially implements the 802.11e MAC mechanism. We simulated the contention-based channel access EDCA mechanism only and have implemented FIFO buffers in every STA which allowed us to calculate throughput, packet delay, jitter and packet loss which are important QoS metrics when measuring and monitoring the level of QoS experienced by STAs. The simulator does not include any PHY operation therefore the only sources of packet loss considered here are either packet drops due to buffer overflow or MAC drops after the maximum number of re-transmission attempts has been reached due to excessive collisions. We did not consider other traffic parameters such as EDCA-TXOP and the "No ACK" policy in simulator. Any STA gaining access to the medium transmits one packet and then releases the channel for the next STA. We considered a BSS infrastructure-type WLAN, hence all the traffic within the WLAN is handled by a single AP, i.e. no direct links or ad-hoc operation have been simulated. We assume no hidden terminals, no mobility in the system and also neglect transmission errors due to noise. Finally, we did not include any high-level management functionality such as beacon frames, association and authentication frames exchanges, etc.

4.1 Simulator Architecture

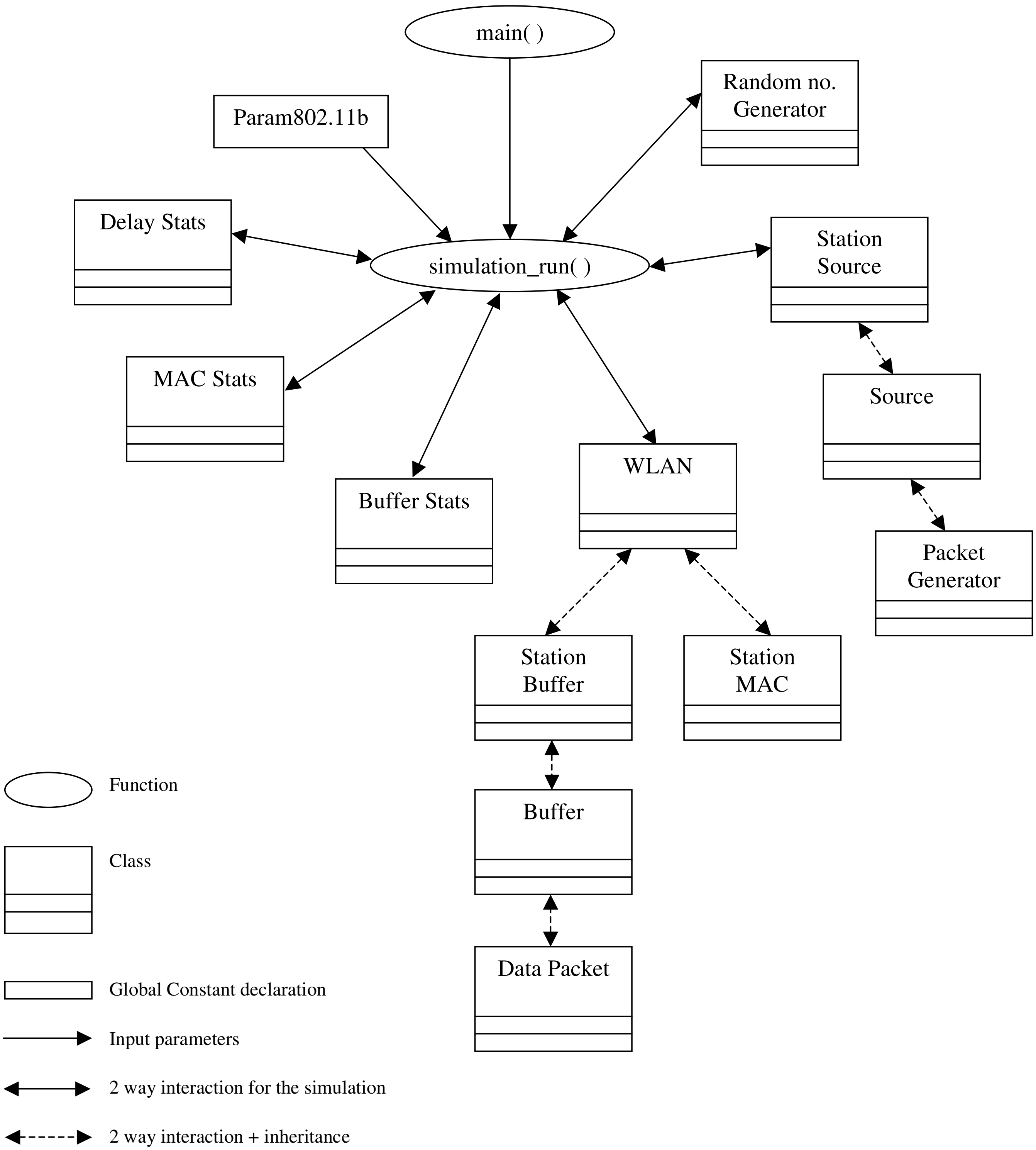

Figure 4.1 Simulator Architecture

4.2 Simulator Overview

4.2.1 Functions and Constants

The initialisation of the simulation takes place in the *main( )* function where a number of different parameters need to be set:

- The simulator gives the option to include three QoS classes (i.e. Gold, Silver and Bronze) and for every class we can define the number of STAs to be simulated.
- The total number of packets to be generated for the simulation.
- The number of Access Categories (ACs) per STA.
- The buffer size for each AC.
- The maximum number of MAC retransmission attempts per STA.
- The AIFS parameter for each AC within each STA.
- The CW_{min} and CW_{max} parameters for each AC within each STA.
- The MSDU size, i.e. packet size for each stream within each STA.
- The MSDU rate, i.e. packet rate for each stream within each STA.
- The packet inter-arrival time for each stream within each STA. The simulator gives the option to choose between constant and exponentially distributed inter-arrival time, i.e. Poisson traffic.

The simulator also gives users the option to set any of these parameters from the command prompt.

These parameters are then passed on to *simulation_run( )* which is the main kernel of the simulator that essentially implements the 802.11e MAC mechanism, i.e. a differentiated CSMA/CA mechanism.

Param802.11b contains parameters declaration for the 802.11b PHY and MAC layers. These parameters are stored as global constants so that they can be accessed anywhere within the simulator.

4.2.2 Classes Overview

- The class *Packet Generator* generates packets according to three parameters:

    - Packet size in bytes.
    - Packet rate in packets per second (pps).
    - Packet inter-arrival time which can be constant or exponentially distributed, i.e. Poisson traffic.

- The class *Source* inherits from *Packet Generator*. There is one *Source* for every STA and it allows the setting and retrieving of the three parameters.

- The class *Station Source* inherits from *Source* and groups all the sources into an array which is used in *simulation_run( )* to access the parameters

- The class *Data Packet* creates data packets (i.e. MSDUs) according to two parameters:

    - Packet length in bytes.
    - Time created (i.e. the time when the packet is emitted from the source).

- The class *Buffer* inherits from *Data Packet* and essentially implements a FIFO buffer according to a fixed buffer size.

- The class *Station Buffer* inherits from *Buffer* and groups all the buffers into an array which is used in *simulation_run( )* to monitor of the buffer size.

- The class *Station MAC* implements STAs according to a set of 802.11e MAC parameters:

  - AIFS, the Arbitration Inter Frame Spacing.
  - Contention Window (CW) size which is an integer number.
  - CW_{min}, the minimum size of CW.
  - CW_{max}, the maximum size of CW.
  - Backoff Counter (BC), a random number drawn from the interval [0, CW].

- The class *WLAN* inherits from *Station MAC* and groups all the STAs into an array which is used in *simulation_run( )* to access the STAs parameters.

- The class *Buffer Stat* collects statistical information about the MAC Buffer, e.g. records the position in the queue where packets are buffered, queue lengths and buffer overflow, etc.

- The class *MAC Stat* collects statistical information on the MAC mechanism, e.g. records the number of transmission attempts it took to successfully transmit a packet or if it was dropped.

- The class *Delay stats* collects statistical information on the delay taken to transmit packets which then is used to calculate the mean delay and jitter.

- The class *Random number Generator* generates random floating point numbers in intervals from 0 to 1 which are then used to calculate the exponentially distributed inter-arrival times for Poisson traffic.

The following figure is a visual representation of the simulator implementation based on the C++ classes.

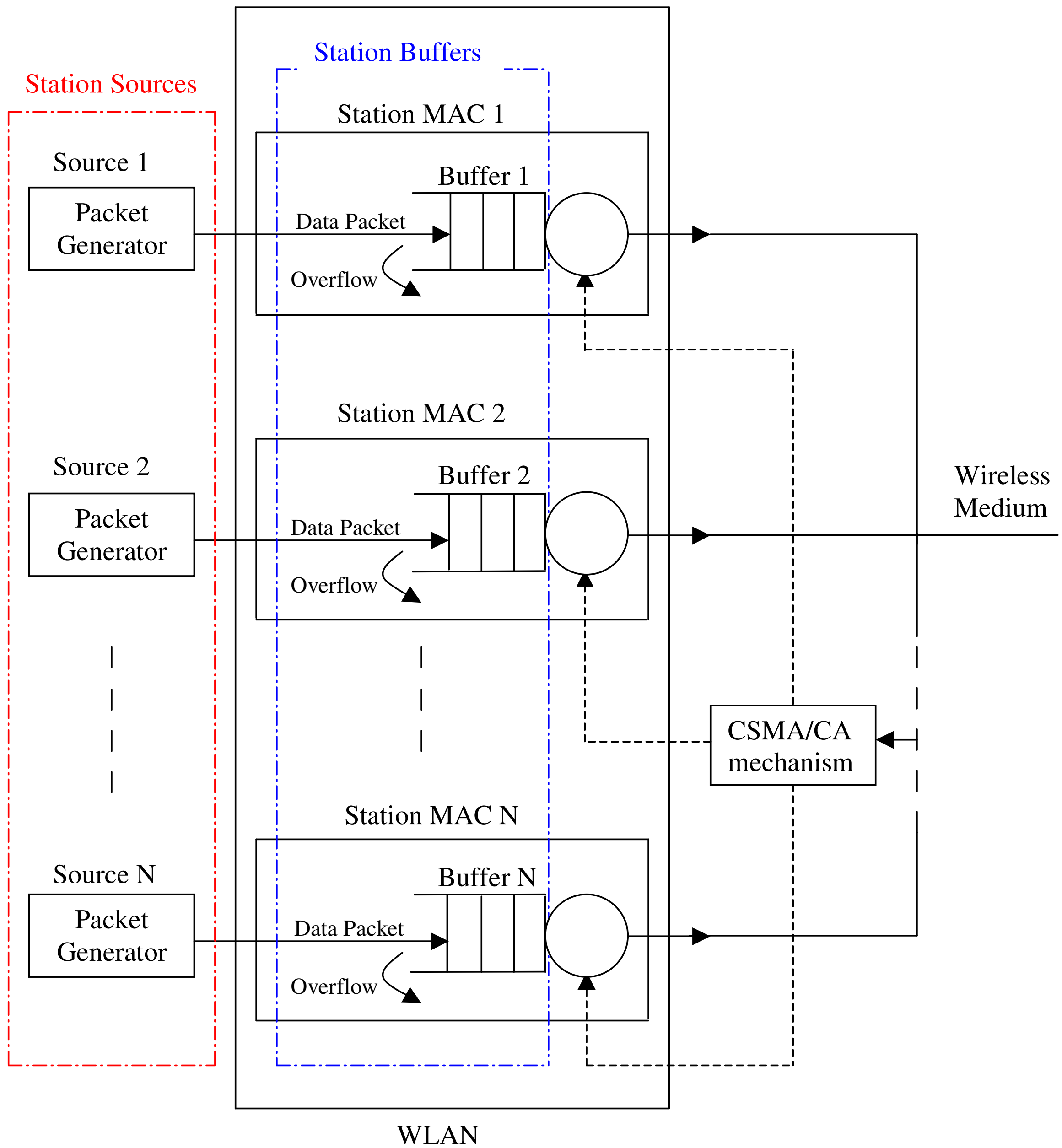

Figure 4.2 Simulator Implementation based on the C++ classes

4.3 Simulation_run( ) Flowchart

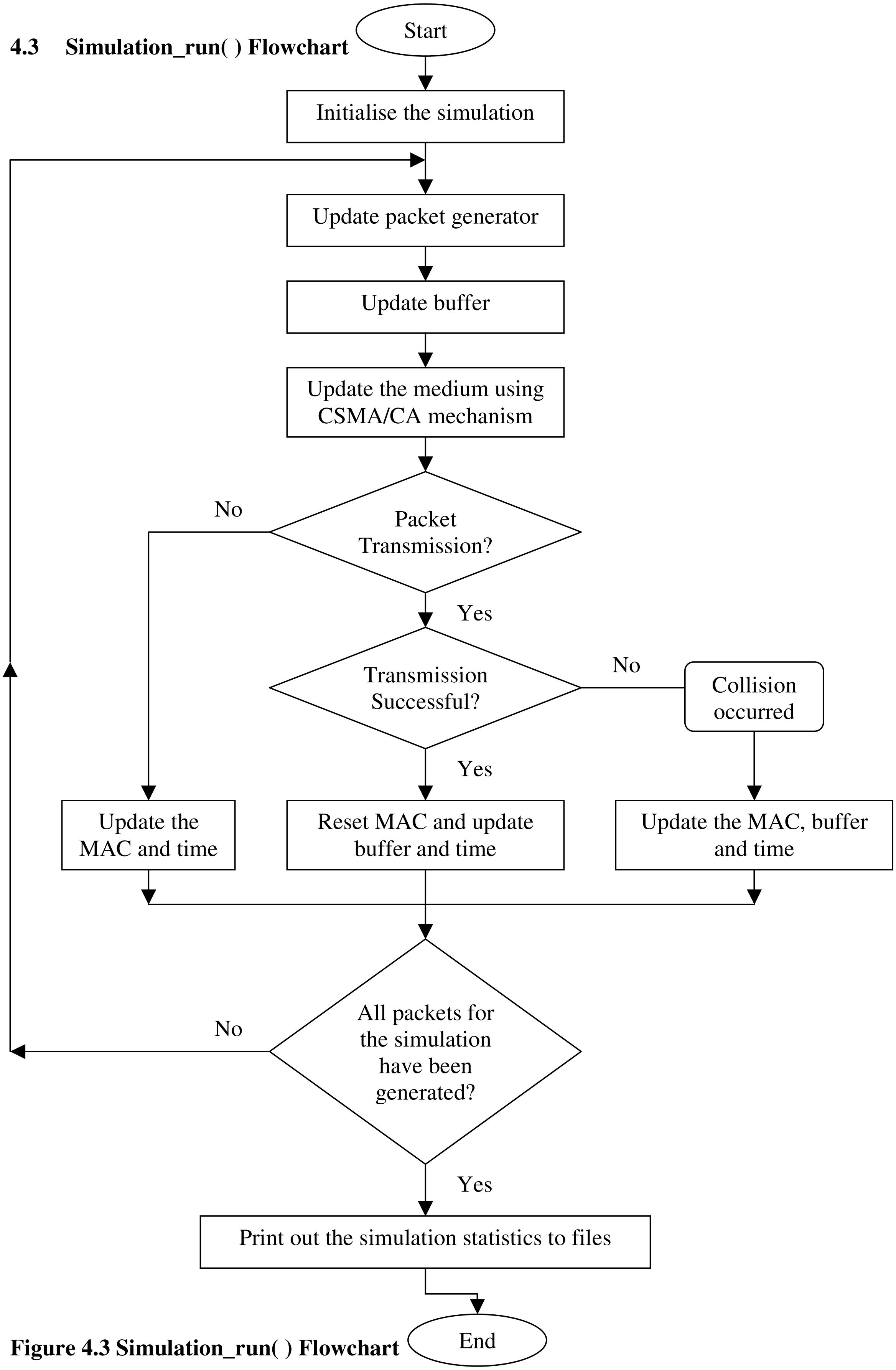

Figure 4.3 Simulation_run( ) Flowchart

4.3.1 Flowchart Description

Initialise the simulation:

First *simulation_run( )* receives input parameters (i.e. number of STAs, buffer size, number of packets to transmit, etc.) from *main( )* and *Param802.11b*.

Output files are then created and opened for the output simulation statistics.

Next objects of the following classes (*WLAN*, *Station Source*, *MAC Stats*, *Buffer Stats*, *Delay Stats* and *Random number Generator)* are instantiated with the input parameters. The class *WLAN* will in turn instantiate more objects of classes *Station MAC* and *Station Buffer* which will create the STAs and their associated buffers respectively. The class *Station Source* will also instantiate more objects of class *Source* which will create a packet generator for every STA. The classes *MAC Stats*, *Buffer Stats* and *Delay Stats* will then be used to monitor the operating/performance statistics of the MAC, buffers and delays respectively for every STA. Next the class *Random number Generator* will be used to calculate exponentially distributed inter-arrival times for Poisson traffic.

Finally numerous counters for the simulation are created and initialised.

Update packet generator:

To generate a new packet, the packet inter-arrival time may be set to constant or exponentially distributed. Once the packet inter-arrival time has elapsed, the packet is generated, i.e. the packet size is set, the time the packet is generated is recorded and the count number of packets generated is incremented.

Update buffer:

To buffer a new packet, the queue size in the buffer must be first checked. If the buffer is not full, the packet is buffered otherwise the packet is dropped. In the case of a packet being buffered, the queue size is decremented and the count number of packets buffered is incremented. If the packet is dropped (i.e. gives rise to buffer loss), the buffer overflow count is incremented.

Update the medium using CSMA/CA mechanism:

For a STA to transmit a packet, it must first set its BC. The STA can only set its BC if the medium has been idle for at least AIFS. It can then decrement its BC by one time slot if the medium is still idle. Once the STAs BC has reach zero, the STA can proceed to transmit the packet.

Reset the MAC and update the buffer and time:

If the transmission is successful, (i.e. no collisions have occurred) the packet is removed from the buffer and the STA resets its CW size and BC. The simulation time is then updated using the duration of the packet transmission.

Update the MAC, buffer and time:

If the transmission is unsuccessful, (i.e. a collision has occurred) the STAs involved in the collision have to double their CW size and reset their BC. Also if the maximum number of MAC retransmissions attempts of a STA has been exceeded, the STA has to drop the packet from the buffer and reset its CW size. The simulation time in that case is updated with the duration of the collision.

Update the MAC and time:

If no transmissions are taking place, i.e. the medium remains idle; STAs decrement their BC by one time slot. The simulation time in that case is updated with the duration of a time slot.

4.4 Simulator Outputs

4.4.1 Time Intervals Statistics

The simulator calculates a set of time intervals that arise during the course of a simulation run:

- The simulation duration time which is used to calculate statistics such as average throughput, average packet rate and average bit rate, etc.
- The medium Idle time (i.e. when no STAs are transmitting) which further subdivided into two time intervals: Free and Access time.
- The Load time which is the time it takes to transmit a packet on the medium including its acknowledgment.
- The medium Busy time which is the sum of all STAs' Load time.

These times intervals are shown in the following figure:

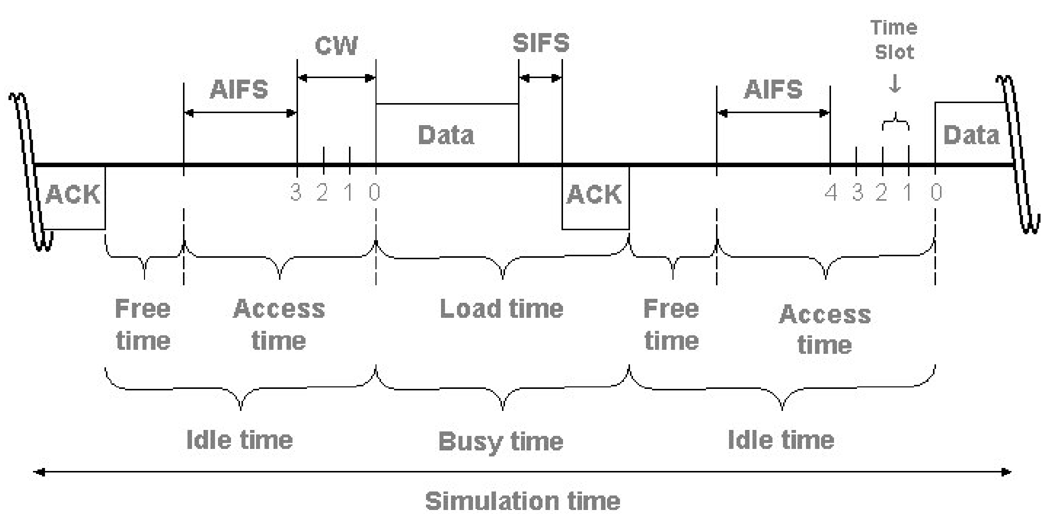

Figure 4.4 Simulation Run Time Intervals

These time intervals are useful in the interpretation and understanding of the operation (and performance) of the 802.11e MAC mechanism and form the basis for the MAC bandwidth component calculations (see equation 3.9).

4.4.2 Station Statistics

The simulator calculates local statistics for each STA from a simulation run:

- The Throughput which is calculated by dividing the total number of bits (or packets) transmitted by a STA by the total duration of a simulation run.

- The average packet delay and jitter which are useful performances statistics that determine the level of QoS experienced by a STA.

- Buffer statistics:

  - Records the position in the queue where packets are buffered. These are collected on a per packet basis. If a STAs packets tend to be buffered at the back of the queue, this means that this STA does not get to transmit often. On the other hand if most of the packets are buffered at the front of the queue, this means that the STA regularly accesses the medium.

  - The buffer loss which is due to buffer overflow (i.e. packets that fail to be buffered) is a useful performance statistic to determine the level of QoS experienced by a STA.

    A nearly full buffer would mean that the network is heavily loaded. In other words, the STA is saturated and packet delay and jitter would be high and the STA will experience a poor QoS. On the other hand a nearly empty buffer would mean that the network is lightly loaded with low packet delay and jitter, i.e. the STA would experience a good QoS.

- MAC statistics:

  - Records the number of transmission attempts it took to successfully transmit a packet. These are collected on a per packet basis. The more transmission attempts it took a STA to successfully transmit a packet means that the STA was involved in many collisions which gives also an indication of the level of congestion on the WLAN.

  - The MAC losses which are due to too many collisions (i.e. the maximum number of re-transmission attempts has been exceeded) is a useful performance statistic to determine the level of QoS experienced by a STA.

    A STA which transmits most of its packets in one or two attempts would mean that the network is lightly loaded with low packet delay and jitter, i.e. the STA would experience a good QoS. On the other hand, a STA transmitting most of its packets in more than two or three attempts would mean that the network is heavily saturated and packet delay and jitter would be high, i.e. the STA would experience a poor QoS.

4.5 Simulation Results

In the next chapter the computer simulator is used to test various scenarios, such as different traffic loads and priorities, in order to assess the effect of varying the 802.11e parameters, namely AIFS and the CW size on QoS provisioning and to investigate the operation (and performance) of the proposed 802.11e MAC mechanism.

Chapter 5

Simulation Results

In this chapter, by using the computer simulation model we investigate the effect of varying two of the 802.11e parameters, namely AIFS and the CW size, on STA differentiation and we validate the assumptions made in section 3.3 about the relationship between the MAC bandwidth components and the nature of their interaction. We proceed by first considering the effect of varying AIFS on QoS provisioning and then proceed to consider the effect of varying the CW size. Finally, we propose a QoS scheme based on a combination of varying both AIFS and CW size.

In the simulations, two wireless STAs using the EDCA mechanism are employed. We assume no hidden terminals, no mobility in the system and also neglect transmission errors due to noise. The simulation uses the 802.11b DSSS PHY standard operating at the maximum rate of 11 Mbit/s to simulate the wireless medium, while the original 802.11 MAC was modified to support the EDCA mechanism. The following table shows the IEEE 802.11b PHY/MAC parameters values used in the simulations:

Parameter	Value
PHY Header	24 bytes
Long PLCP Preamble	192 μs
Long MAC Header	34 bytes
ACK size	14 bytes
Channel Bit Rate	11 Mbit/s
Slot Time	20 μs
SIFS	10 μs
DIFS	50 μs
MAC retransmission limit	10
MAC buffer size	10

Table 5.1 IEEE 802.11b PHY/MAC Parameters used in Simulation

5.1 Effects of varying AIFS

5.1.1 QoS Support

The simulations consist of two wireless STAs (STA_1 and STA_2) carrying identical traffic types. Both STAs generate packets with a packet size equal to 512 bytes and an exponentially distributed inter-arrival time, i.e. Poisson traffic. We have chosen to simulate Poisson traffic, as it is considered to be a reasonable approximation to typical data traffic characteristics and is widely used. Consequently, the simulation results presented here are strictly only valid for Poisson type traffic. However we expect the results to be reasonably indicative for other traffic types. The load presented to the wireless medium by STA_1 is held fixed at 250 pps (packets per second), whereas the load presented by STA_2 is ramped from zero to full saturation in steps of 50 pps. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	STA_1 (Fixed)	STA_2 (Ramping)
AIFSN	2	2,3,4,5,6,7,8
CW_{min}	7	7
CW_{max}	1023	1023

Table 5.2 MAC Parameters for the Two STAs

The mechanism for adjusting the AIFS value is through the AIFSN parameter where AIFSN indicates the number of slots times following a SIFS duration, i.e. AIFS = SIFS + AIFSN × Slot Time.

In the simulations CW_{min} = 7 is used as opposed to the standard specification of CW_{min} = 31 as the improvement in effective throughput when simulating two STAs is quite substantial (i.e. in terms of optimising the throughput) and we have used the maximum possible value for CW_{max} which is 1023.

The following figure shows the performance characteristic of the two wireless STAs, STA_1 and STA_2 in terms of their combined loads (BW_{load}), BW_{free} and Packet Loss Rate (PLR) as a function of STA_2's offered load when using the legacy DCF, i.e. AIFS = DIFS for both STAs.

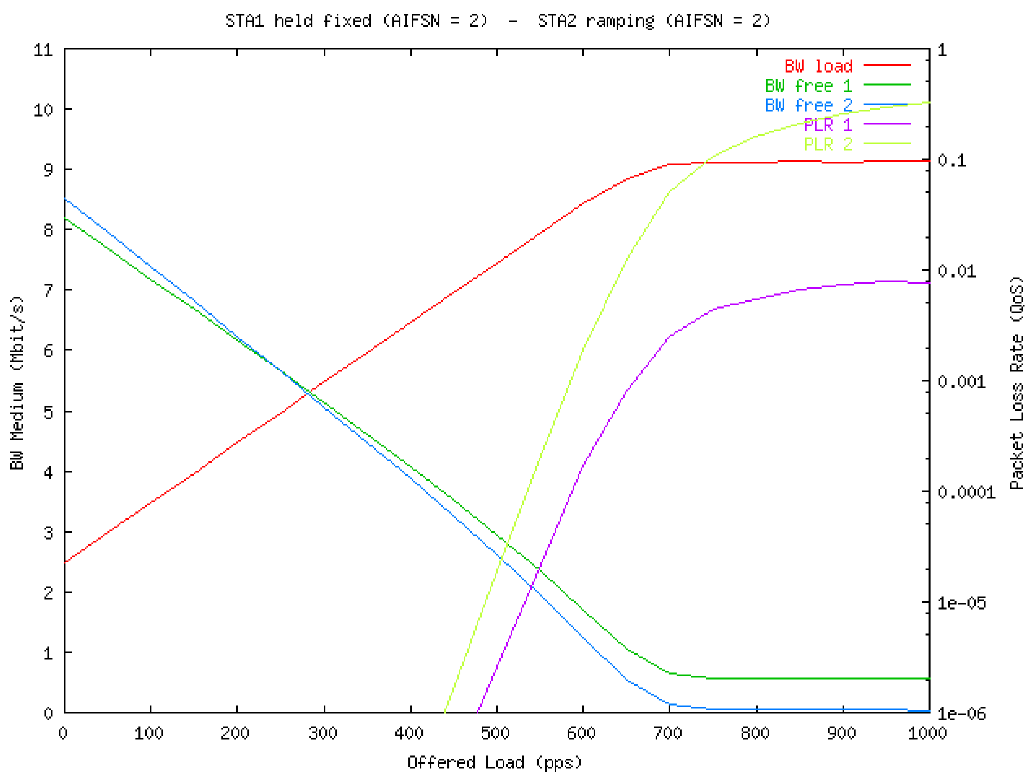

Figure 5.1 Legacy DCF for both STAs

When the combined load (BW_{load}) of STA_1 and STA_2 is small, both STAs have sufficient BW_{free} and hence both STAs experience a high QoS (i.e. negligible PLR). As the load from STA_2 increases both STAs experience a reduced BW_{free} until a point is reached where the QoS experienced by STA_2 begins to deteriorate (i.e. the PLR for STA_2 rises dramatically). As the load presented by STA_2 continues to increase, quickly a point is reached where it begins to noticeably impact on the performance of STA_1, i.e. its QoS starts to deteriorate. This point represents the onset of network saturation where both STAs no longer have sufficient BW_{free} and hence both STAs experience poor QoS. Here it is clear that when using the legacy DCF, STA_2's offered load impacts on the QoS of STA_1 as the two STAs contend for the wireless medium with the same priority. Consequently, if the legacy DCF were to be deployed in a hotspot scenario, for example, it would not be possible to offer a differentiated QoS service to the users. Therefore, we propose to adjust the AIFS parameter to illustrate how the interaction between the MAC bandwidth components may be controlled in order to prioritise STA_1 over STA_2.

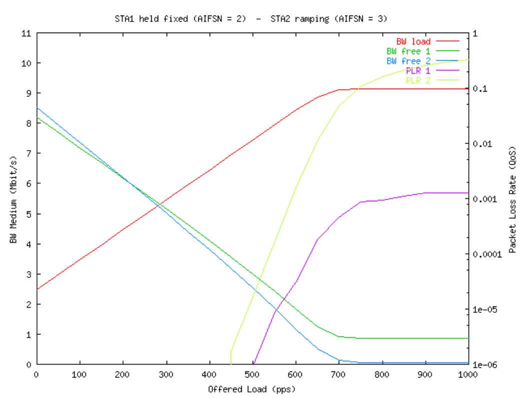

Figure 5.2 AIFSN = 3 for STA_2

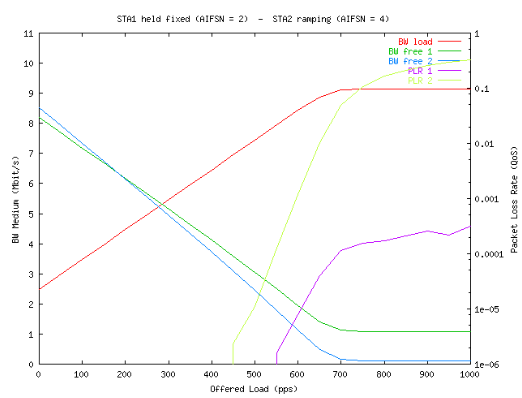

Figure 5.3 AIFSN = 4 for STA_2

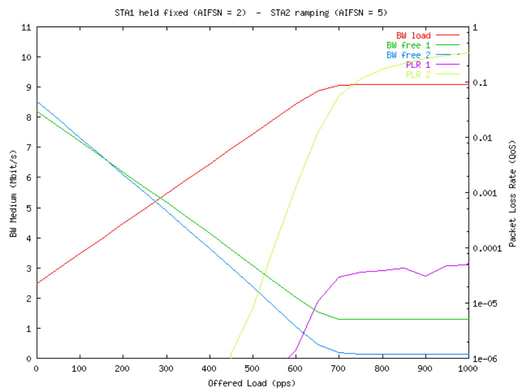

Figure 5.4 AIFSN = 5 for STA$_2$

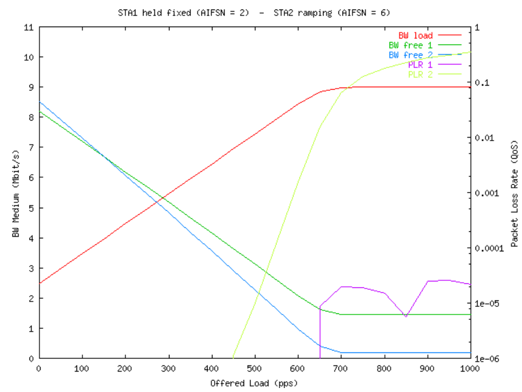

Figure 5.5 AIFSN = 6 for STA$_2$

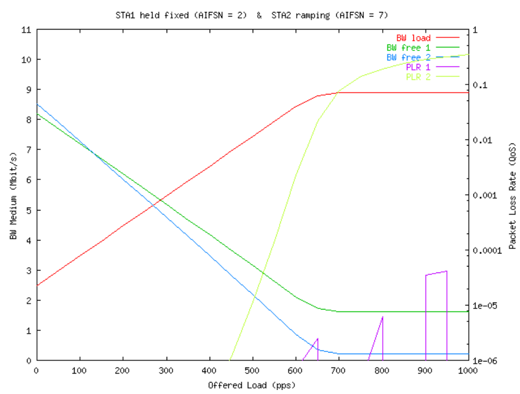

Figure 5.6 AIFSN = 7 for STA$_2$

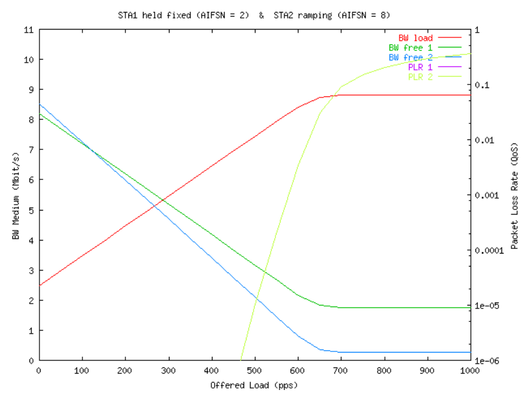

Figure 5.7 AIFSN = 8 for STA$_2$

We can clearly see that as AIFSN increases for STA$_2$ (i.e. as its priority decreases), STA$_1$'s PLR improves and eventually becomes negligible ($<10^{-6}$) in Figure 5.7. This is as a result of STA$_1$ experiencing a significant amount of BW$_{free}$ resulting in a negligible PLR. This indicates that the network resources are no longer equally shared between the two stations. It can also be seen that the combined load (BW$_{load}$) is decreasing since STA$_2$ is not transmitting as much given that its access requirements is increasing. The shape of PLR$_1$ in Figure 5.6 is due to the fact that the simulation run is not long enough despite being run for 10 millions packets. A longer simulation run would produce better results for these very low PLR. The above results confirm that by varying AIFS it is possible to control the interaction between the MAC bandwidth components in order to prioritise a particular STA over another and thereby improve its QoS.

5.1.2 "Nailing-up" Bandwidth

By the term "nailing-up" we mean that a particular STA is given priority over another STA in terms of gaining access to the medium which ultimately results in bandwidth being reserved for that particular STA. It should be noted that it is not possible to assign a fixed bandwidth to a STA in a wireless network as the CSMA/CA mechanism is a bandwidth on demand service.

We use the same test scenario as described in section 5.1.1 but instead both STAs are ramping from zero to full saturation. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	**STA_1**	**STA_2**
AIFSN	2	2,4,6,8,10
CW_{min}	7	7
CW_{max}	1023	1023

Table 5.3 MAC Parameters for the Two STAs

The following figure shows the performance characteristics of STA_1 and STA_2 in terms of their throughput and PLR as a function of the offered load when using the legacy DCF, i.e. AIFS = DIFS for both STAs.

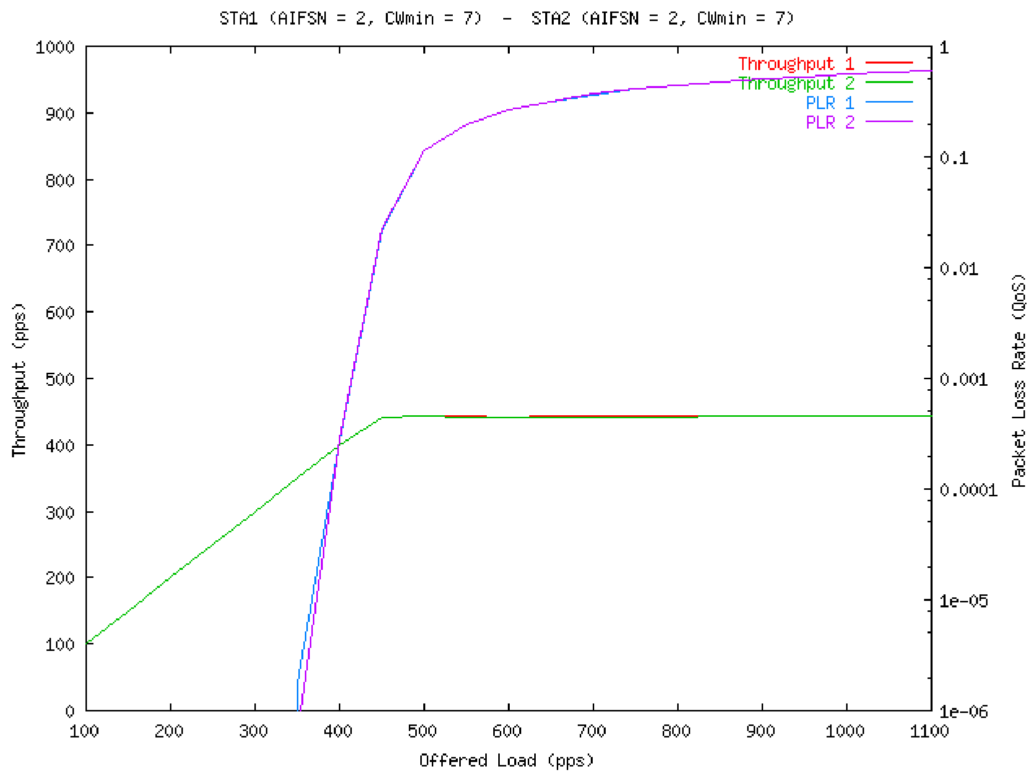

Figure 5.8 Legacy DCF for both STAs

When using the legacy DCF both STAs experience the same throughput and PLR as the two STAs contend for the wireless medium with the same priority. Therefore, We propose to adjust the AIFS parameter to prioritise STA_1 over STA_2 and to monitor the throughput and PLR experienced by both STAs.

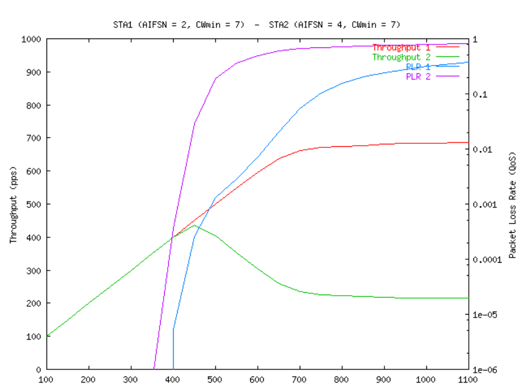

Figure 5.9 AIFSN = 4 for STA_2

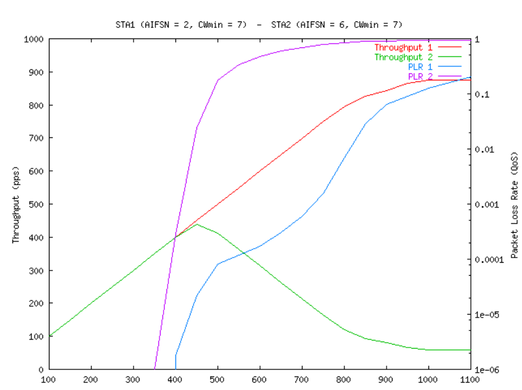

Figure 5.10 AIFSN = 6 for STA_2

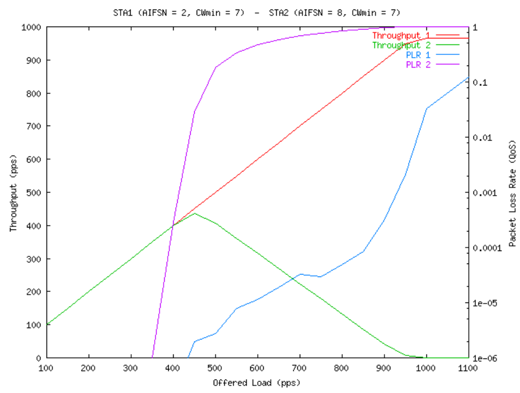

Figure 5.11 AIFSN = 8 for STA_2

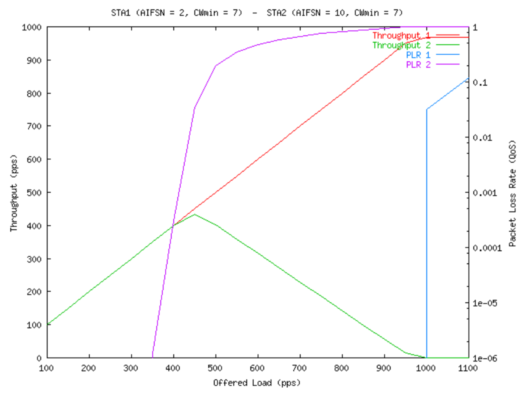

Figure 5.12 AIFSN = 10 for STA_2

We can clearly see that as AIFSN increases for STA_2 (i.e. as its priority decreases) both STAs are experiencing different throughputs and PLRs. Indeed the throughput of STA_1 is increasing up to the point of medium saturation (i.e. until there is no more bandwidth available) and its PLR is decreasing and eventually becomes negligible. In Figure 5.12 STA_1 is the only station transmitting (see non-overlapping contention processes scenario described below) which means that STA_1 and the whole network saturates together hence the abrupt rise of PLR_1. Whereas for STA_2 its throughput is decreasing with a large PLR (rendering the performance unusable). The reason for this is that the two STAs are not equally sharing the available bandwidth in the wireless medium since STA_1 has priority over STA_2 when accessing the medium hence giving the opportunity for STA_1 to use as much bandwidth as it requires. Hence this shows that it is possible to "nail-up" bandwidth for a STA by varying the AIFS parameter. The following example explains how this is done.

In Figure 5.12, STA_1 is able to use up all the bandwidth available in the wireless network due to the setting of the AIFSN parameter, i.e. when AIFSN = 10 for STA_2 this gives STA_1 exclusive access to the medium. Indeed if STA_1 were to pick 7, the highest possible value for its backoff counter (BC) (i.e. random number drawn between 0 and CW_{min} = 7) STA_1 would have to wait for $AIFS_1$ plus 7 slots before transmitting, i.e. 190μs:

$$T_{AIFS1} = SIFS + AIFSN_1 \times Time\ Slot$$
$$= 10+2\times20 \quad \text{(equation 5.1)}$$
$$= 50\ \mu s$$

$$T_{BC1} = CW_{min} \times Time\ Slot$$
$$= 7\times20 \quad \text{(equation 5.2)}$$
$$= 140\ \mu s$$

$$T_{tx1} = T_{AIFS1} + T_{BC1}$$
$$= 50+140 \quad \text{(equation 5.3)}$$
$$= 190\ \mu s$$

Whereas if STA_2 were to simultaneously pick 0, the lowest possible value for its BC, STA_2 would have to wait for $AIFS_2$ before transmitting, i.e. 210μs. Therefore the two STAs will never directly contend with one another in order to access the medium, i.e. this is a non-overlapping contention processes scenario.

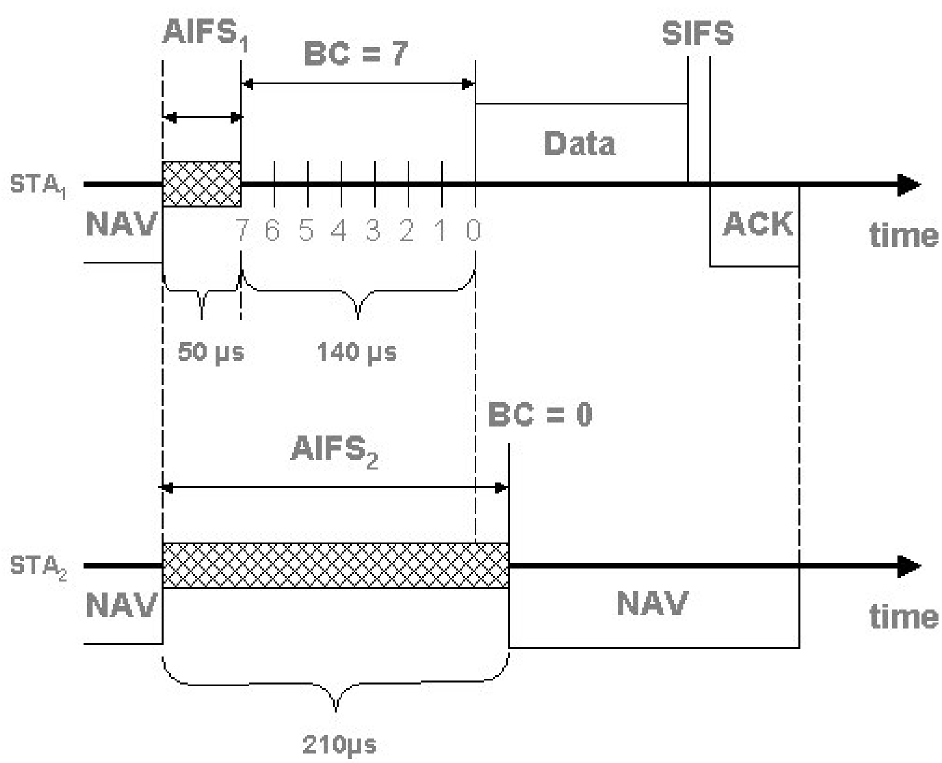

Figure 5.13 Non-overlapping Contention Processes Scenario

On the other hand if AIFSN for STA_2 were set to 9 in this particular scenario, both STAs would attempt to transmit at the same time which would result in a collision requiring both STAs to double the size of their respective contention windows(CWs) and reattempt access.

5.1.3 Region of QoS Differentiation

In order to identify the region of QoS differentiation we need to look at the capacities as experienced by both STAs. We define the term capacity as being the maximum offered load of a STA that satisfies a given QoS requirement, e.g. PLR < 10^{-4}.

We use the same test scenario as described in section 5.1.1 but instead STA_1 is ramping from zero to full saturation and STA_2 is held fixed at 400 pps. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	**STA_1**	**STA_2**
AIFSN	2	4,6,8
CW_{min}	7	7
CW_{max}	1023	1023

Table 5.4 MAC Parameters for the Two STAs

The following figure shows the performance characteristics of STA_1 and STA_2 in terms of their throughput and PLR as a function of STA_1's offered load.

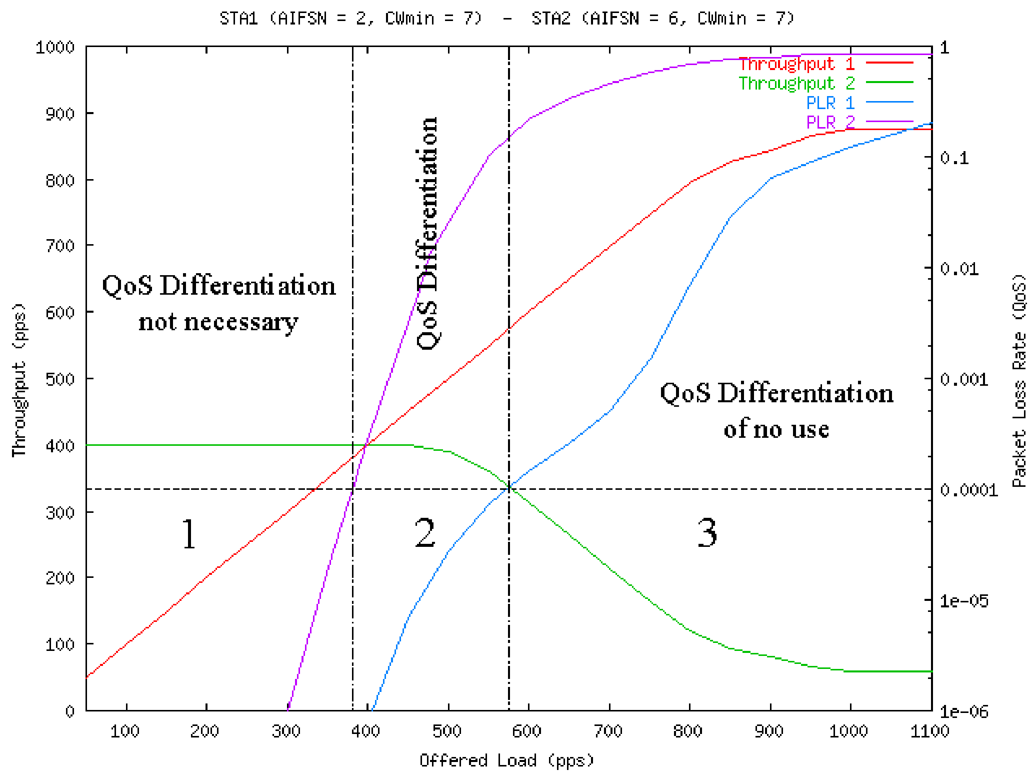

Figure 5.14 Regions of QoS Differentiation

We assume a PLR of less than 10^{-4} (typical PLR requirement) as the QoS requirement in the following. We can see that in region 1 both STAs experience the same capacity as the total offered load is less than the available capacity, i.e. there is sufficient bandwidth available to support both STAs offered loads therefore there is no need for QoS differentiation. In region 2 the medium starts to saturate and the effects of QoS differentiation become apparent. In region 2 the capacity of STA_1 is greater than that of STA_2, i.e. 570 pps and 380 pps respectively. Here the total offered load is approximately equal to the available capacity, therefore some of the available bandwidth has been taken from STA_2 and given to STA_1. In region 3 the total offered load exceeds the available capacity, i.e. there is insufficient bandwidth to support both offered loads and consequently both STAs no longer meet their QoS requirements of PLR $\leq 10^{-4}$, therefore the differentiation mechanism is no longer of any use.

This is to be expected as the introduction of a differentiated service scheme cannot create additional bandwidth, instead the available resources are allocated to the competing STAs on a priority basis.

Next we propose to prioritise STA_1 over STA_2 and to monitor the effects on the region of QoS differentiation.

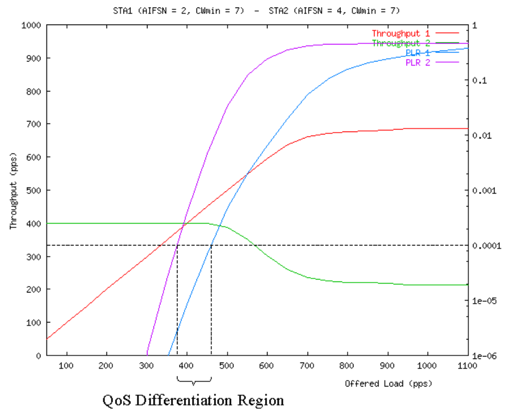

Figure 5.15 AIFSN = 4 for STA_2

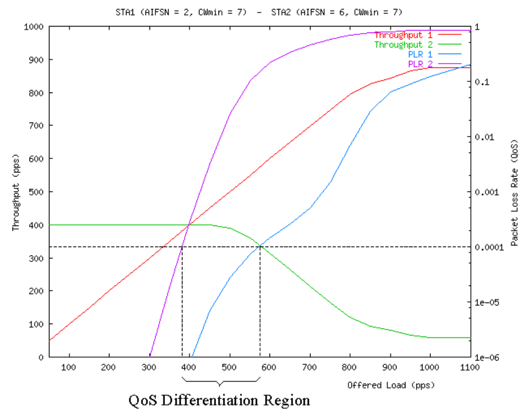

Figure 5.16 AIFSN = 6 for STA_2

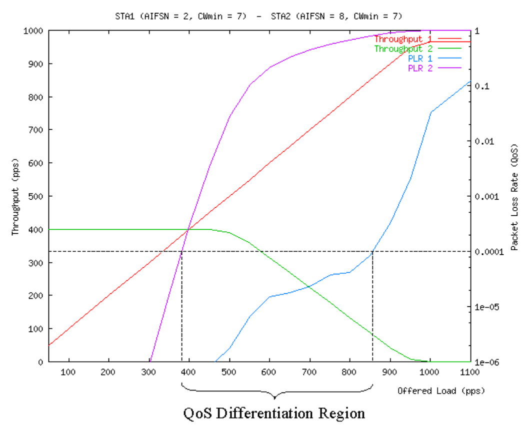

Figure 5.17 AIFSN = 8 for STA_2

We can clearly see that as AIFSN increases for STA_2, the region of effective QoS differentiation expands and the capacity of STA_1 increases from 460 pps to 860 pps whereas STA_2 capacity stays fixed at 380 pps. This is an interesting result which shows the direct effect of varying AIFS on QoS differentiation. Indeed this demonstrates how AIFS can be altered in order to guarantee a different set of capacities with QoS requirements. We can also deduce that it is necessary to know the offered load of a particular STA or class of service in order to set the AIFSN values correspondingly.

This could be applied to a hotspot scenario, where an operator would need some indication of the expected traffic load from a user in order to allocate priority bandwidth with QoS requirements to that user. Since the traffic load will be continually varying there will also be a requirement to continually update the AIFSN values.

5.2 Effects of varying CW_{min}

5.2.1 QoS Support

We use the same scenario as described in section 5.1.1 (i.e. STA_1 is held fixed at 250 pps and STA_2 is ramping from zero to full saturation) but instead we propose to reduce the priority of STA_2 by increasing its CW_{min} value. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	STA_1 (Fixed)	STA_2 (Ramping)
AIFSN	2	2
CW_{min}	7	7, 15, 31
CW_{max}	1023	1023

Table 5.5 MAC Parameters for the Two STAs

The following figures show the performance characteristics of STA_1 and STA_2 in terms of their combined BW_{load}, BW_{free} and PLR as a function of STA_2's offered load.

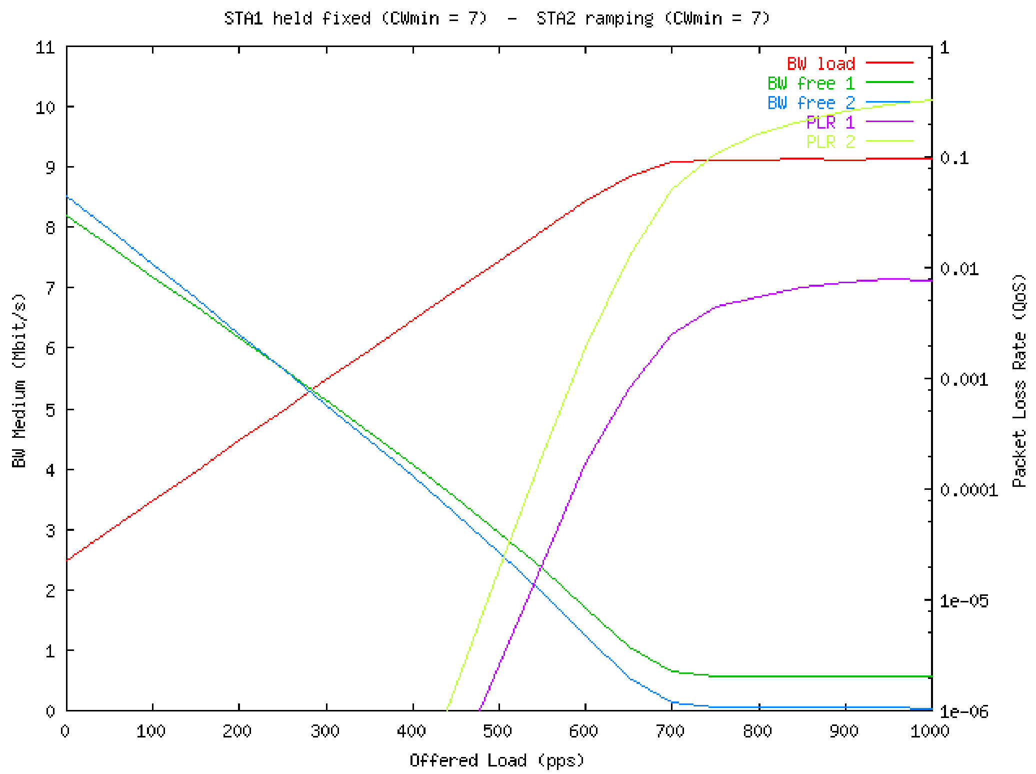

Figure 5.18 CW_{min} = 7 for both STAs

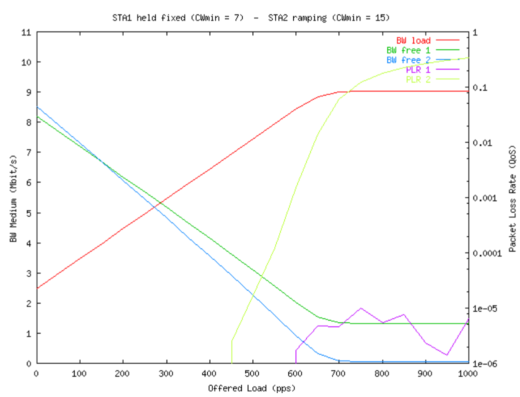

Figure 5.19 CW_{min} = 15 for STA_2

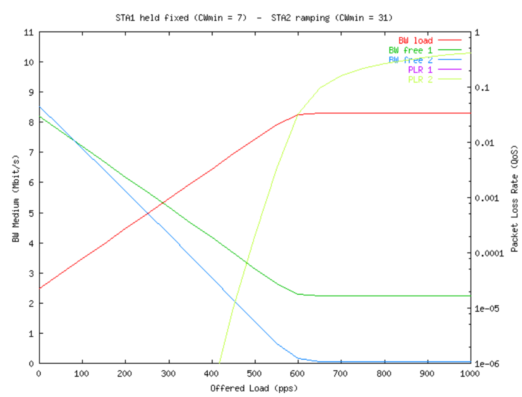

Figure 5.20 CW_{min} = 31 for STA_2

We can clearly see that as CW_{min} increases for STA_2 (i.e. as its priority decreases), STA_1's PLR improves and becomes negligible ($<10^{-6}$) in Figure 5.20. This is due to the same reason as described in section 5.1.1, i.e. STA_1 experiences a significant amount of BW_{free} resulting in a negligible PLR. We can also notice that CW_{min} is a coarser parameter on QoS provisioning than AIFS as the amount of BW_{free} available for STA_1 is greater than when using AIFS and the decrease in the combined load is also more pronounced. The above results confirm that by varying CW_{min} it is possible to control the interaction between the MAC bandwidth components in order to prioritise a particular STA over another and thereby improve its QoS.

5.2.2 "Nailing-up" Bandwidth

We use the same scenario as described in section 5.1.2. (i.e. both STAs are ramping from zero to full saturation) but instead we propose to reduce the priority of STA_2 by increasing its CW_{min}. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	STA_1	STA_2
AIFSN	2	2
CW_{min}	7	7,15,31,63,127
CW_{max}	1023	1023

Table 5.6 MAC Parameters for the Two STAs

The following figures show the performance characteristics of STA_1 and STA_2 in terms of their throughput and PLR as a function of the offered load.

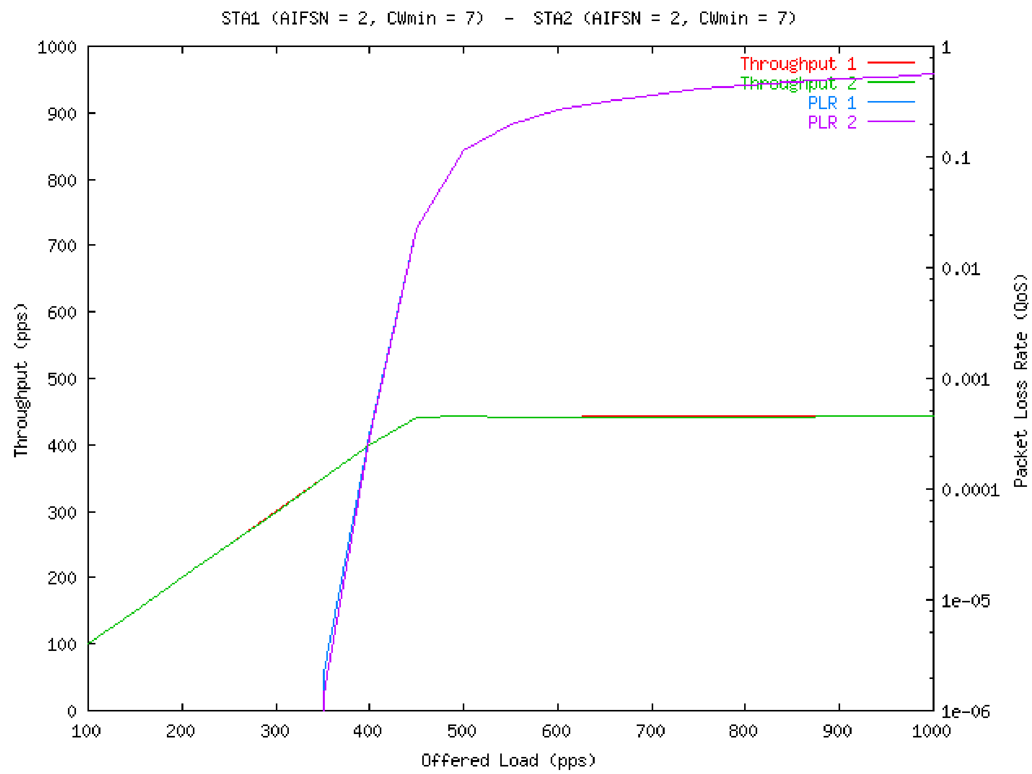

Figure 5.21 CW$_{min}$ = 7 for both STAs

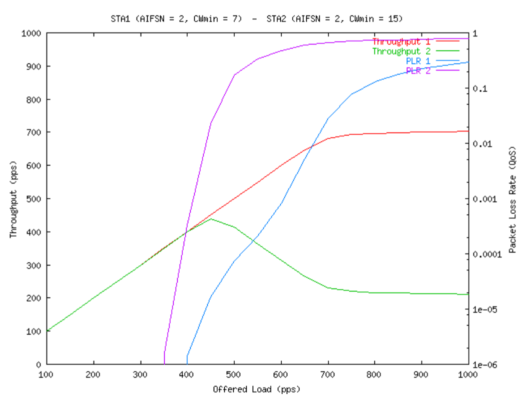

Figure 5.22 CW$_{min}$ = 15 for STA$_2$

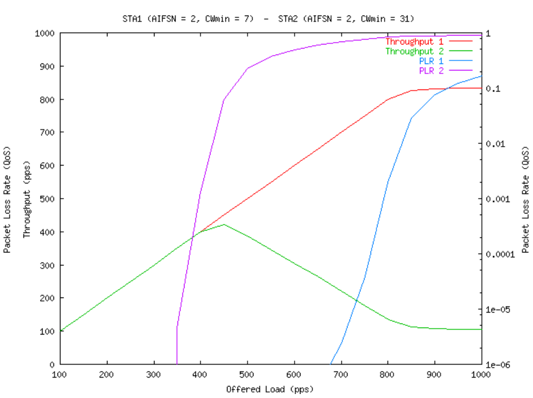

Figure 5.23 CW$_{min}$ = 31 for STA$_2$

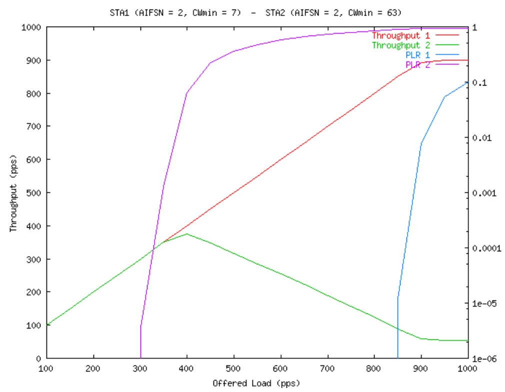

Figure 5.24 CW$_{min}$ = 63 for STA$_2$

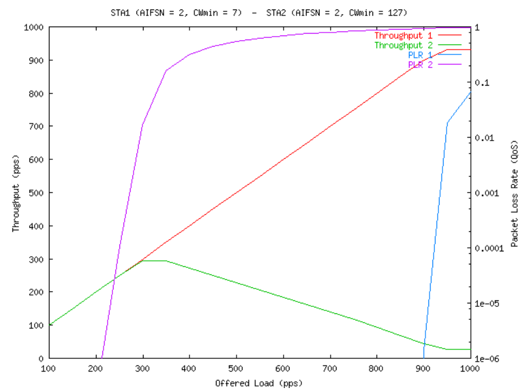

Figure 5.25 CW$_{min}$ = 127 for STA$_2$

We can clearly see that as CW$_{min}$ increases for STA$_2$ (i.e. as its priority decreases) both STAs are experiencing different throughputs and PLRs. Indeed the throughput of STA$_1$ is increasing up to medium saturation (i.e. until there is no more bandwidth available) and its PLR is decreasing. Whereas for STA$_2$ its throughput is decreasing and its PLR is increasing. This is due to the same reason as described in section 5.1.2, i.e. the two STAs are not equally sharing the available bandwidth in the wireless medium since STA$_1$ has priority over STA$_2$ when accessing the medium hence giving STA$_1$ the opportunity to use up more bandwidth than STA$_2$. Therefore it is also possible to "nail-up" bandwidth for a STA by varying CW$_{min}$ but it should be noted that the differentiation is not as pronounced, i.e. STA$_2$'s throughput is not forced to zero as when varying AIFS. On the other hand we can see that the point of onset of severe PLR for STA$_1$ occurs later (but does not become negligible) compared with the case when AIFS is varied. We can also see that the gain in throughput for STA$_1$ is not as effective since some of the available bandwidth is being wasted when using excessively high values for CW$_{min}$.

5.2.3 Region of QoS Differentiation

We use the same scenario as described in section 5.1.3 but instead we propose to prioritise STA_1 over STA_2 and to monitor the effects on the region of QoS differentiation. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	**STA_1**	**STA_2**
AIFSN	2	2
CW_{min}	7	15,31,63
CW_{max}	1023	1023

Table 5.7 MAC Parameters for the Two STAs

The following figures show the performance characteristics of STA_1 and STA_2 in terms of their throughput and PLR as a function of the offered load.

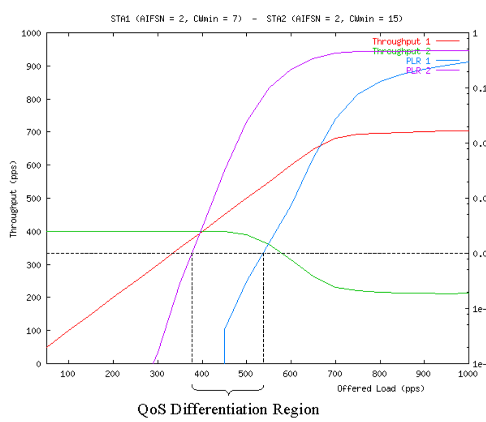

Figure 5.26 CW_{min} = 15 for STA_2

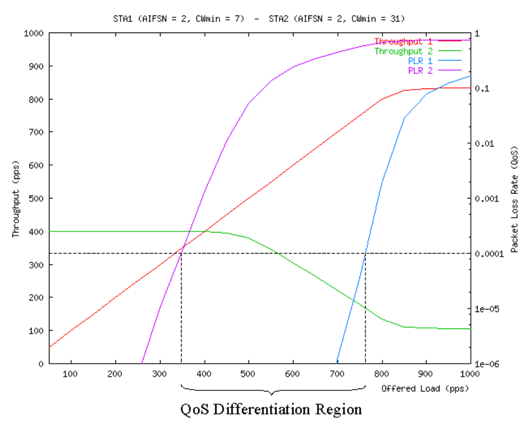

Figure 5.27 CW_{min} = 31 for STA_2

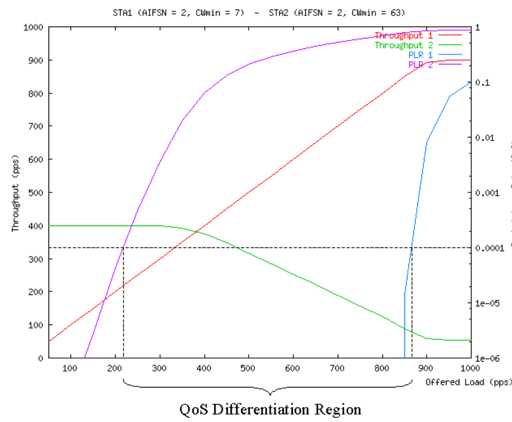

Figure 5.28 CW_{min} = 63 for STA_2

We can see from these results that CW_{min} has the same effect as AIFS on QoS differentiation therefore the same conclusions can be drawn. We can see that as CW_{min} increases for STA_2, the region of QoS differentiation also expands, i.e. the capacity of STA_1 increases but the difference with AIFS is that STA_2 capacity simultaneously decreases which makes the region of differentiation even wider. It should also be noted that STA_1 capacity improves faster than when using AIFS which confirms that CW_{min} is a coarser parameter on QoS differentiation than AIFS.

5.3 Combining AIFS and CW_{min}

We use the same test scenario as described in section 5.1.2. (i.e. both STAs are ramping from zero to full saturation) but instead we propose to reduce the priority of STA_2 by increasing both AIFS and CW_{min} and to monitor the throughput and PLR experienced by both STAs. The following table shows the MAC parameters selected for the two STAs in the simulations:

Parameters	STA_1	STA_2
AIFSN	2	6
CW_{min}	7	31
CW_{max}	1023	1023

Table 5.8 MAC Parameters for the Two STAs

The following figures show the STA differentiation obtained by varying just AIFS or CW_{min} and then by varying both AIFS and CW_{min}. The performance characteristics of STA_1 and STA_2 in terms of their throughput and PLR as a function of the offered load is shown.

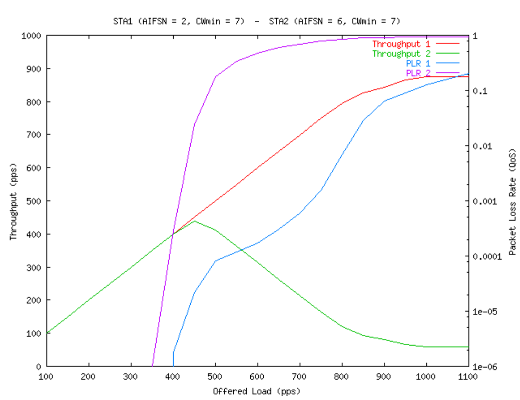

Figure 5.29 AIFS = 6 for STA_2

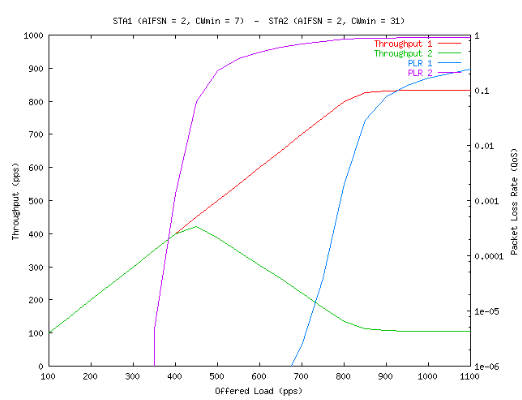

Figure 5.30 CW_{min} = 31 for STA_2

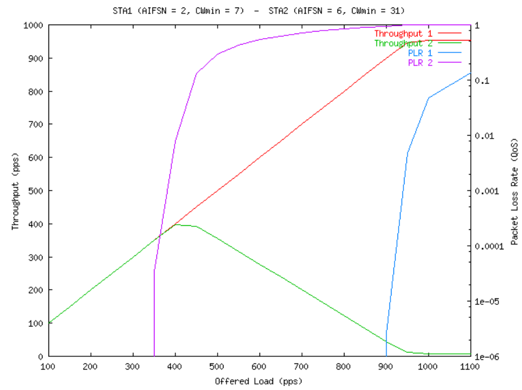

Figure 5.31 AIFS = 6 and CW_{min} = 31 for STA_2

We can clearly see the advantage of combining both AIFS and CW_{min} over varying either AIFS or CW_{min} on its own on the STA differentiation. We can see in Figure 5.31 that STA_1 has a higher throughput since STA_2's throughput is forced to zero and we can also see that the onset of severe PLR for STA_1 happens at a higher offered load than in Figure 5.29 and 5.30.

From the previous results it appears that CW_{min} is a coarser tuning parameter when differentiating between STAs whereas AIFS appears to be a finer tuning parameter. The combination of varying both AIFS and CW_{min} is next employed to establish a class-based differentiated service QoS scheme, e.g. a Gold class, a Silver class and a Bronze class of service.

5.4 Class-based Differentiated Service (CBDS) QoS Scheme

A CBDS QoS scheme should be set up in such a way that at all times, all STAs belonging to a higher priority class (irrespective of the number of STAs, traffic types, network load conditions, etc.) will always experience a better service than STAs belonging to lower priority classes. We show how the AIFS and CW_{min} parameters can be set so as to establish such a QoS scheme.

We propose to examine a scenario which comprises three QoS classes with three STAs having different priorities within each class. Here, we define the QoS condition as being that all STAs in a given class experience a higher throughput than STAs in a class of lower priority. All STAs generate packets with packet size equal to 512 bytes and an exponentially distributed inter-arrival time, i.e. Poisson traffic. The load presented to the wireless medium by all STAs is ramped from zero to full saturation in steps of 50 pps.

We consider two cases. In the first case we use CW_{min} to set the boundaries between the classes and we use AIFS to fine tune, i.e. differentiate between the STAs within a class. Whereas in the second case we do the opposite, i.e. we use AIFS to set up the class boundaries and CW_{min} to fine tune within a class.

Case 1:

The following table shows the MAC parameters used in the simulation to set the class boundaries and to differentiate between the STAs:

	Gold class (CW_{min} = 7)	**Silver class (CW_{min} = 15)**	**Bronze class (CW_{min} = 31)**
STA_1	AIFSN = 2	AIFSN = 2	AIFSN = 2
STA_2	AIFSN = 4	AIFSN = 4	AIFSN = 4
STA_3	AIFSN = 6	AIFSN = 6	AIFSN = 6

CW_{max} = 1023 for all STAs.

Table 5.9 Case 1 Parameters

The following figure shows the performance characteristics of the wireless STAs in terms of their throughput as a function of the offered load.

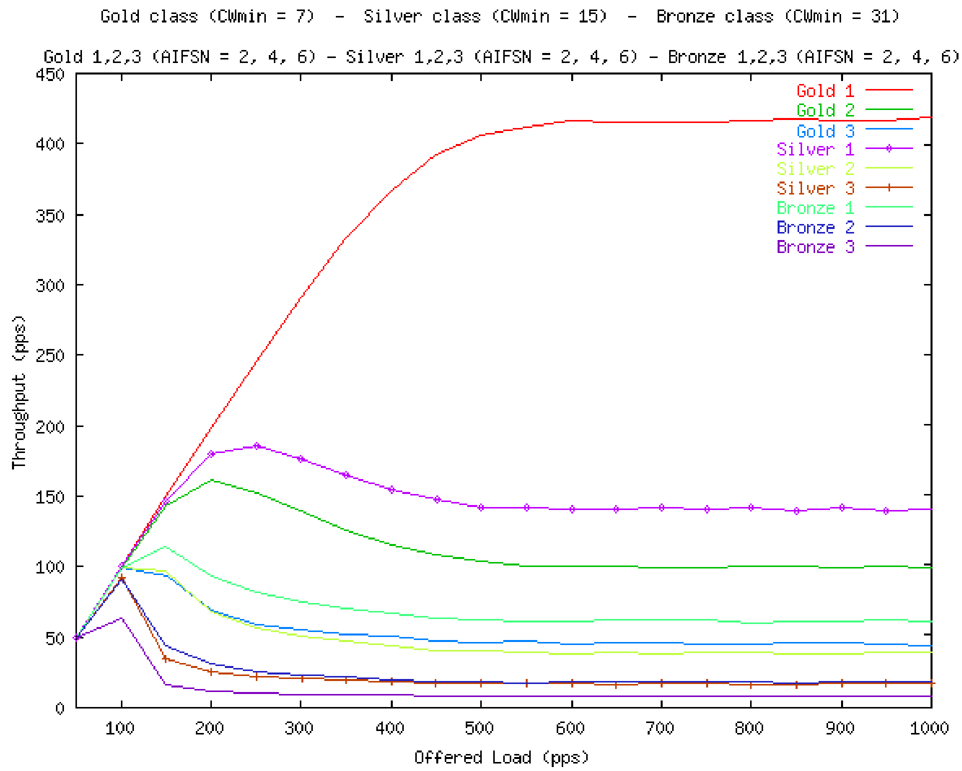

Figure 5.32 Case 1 Throughput

We can see from this figure that the QoS condition defined above is not respected, STA_1 belonging to the Silver class (STA_{S1}) experiences a better throughput than STA_2 and STA_3 of the Gold class (STA_{G2} and STA_{G3}). This is also the case for the Silver class, STA_1 belonging to the Bronze class (STA_{B1}) experiences a better throughput than STA_{S2} and STA_{S3}.

When plotting the PLR we can see that the same problem appears, i.e. the QoS condition is not respected.

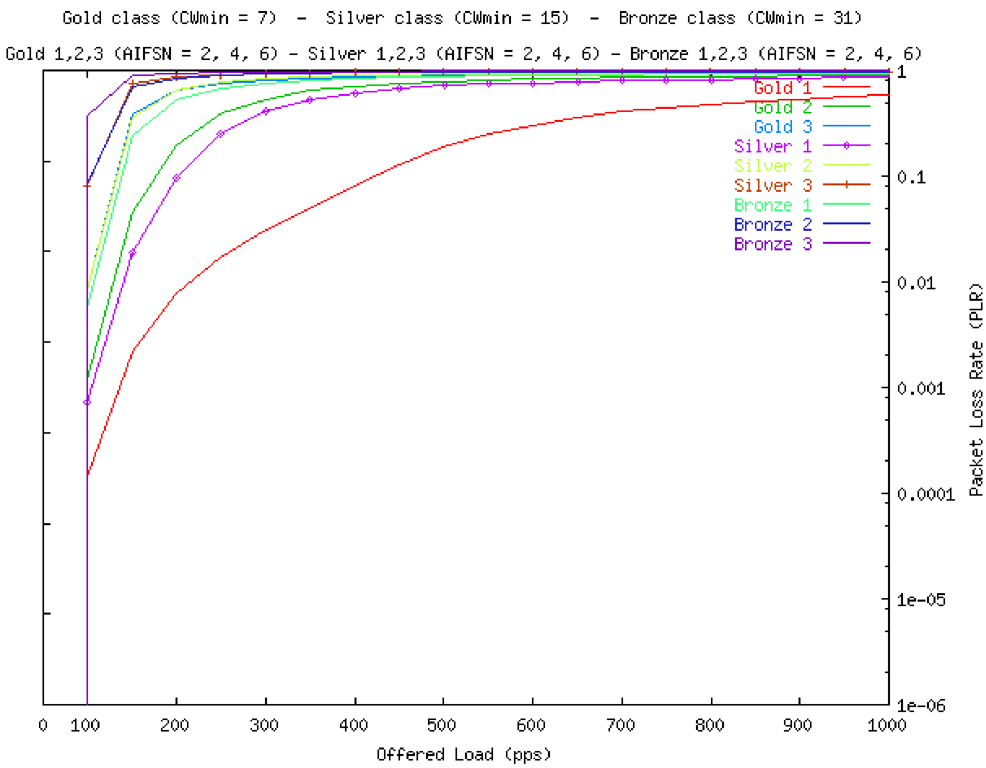

Figure 5.33 Case 1 PLR

We can also see that all 9 STAs are experiencing a poor PLR.

To remedy to this problem we could use a larger value of CW_{min} for the Silver and Bronze classes, i.e. CW_{min} = 31 and CW_{min} = 127 respectively but this is not an optimal solution as we cannot ensure that the QoS condition will be respected in every case. Moreover, in the case where there are more than three QoS classes we would run out of CW_{min} values. A better approach to solving the problem is to use AIFS to set the class boundaries and CW_{min} to differentiate between the STAs within a class. This leads us to the second case.

Case 2:

The following table shows the MAC parameters used in the simulation to set the class boundaries and to differentiate between the STAs:

	Gold class (AIFSN = 2)	Silver class (AIFSN = 34)	Bronze class (AIFSN = 66)
STA_1	$CW_{min} = 7$	$CW_{min} = 7$	$CW_{min} = 7$
STA_2	$CW_{min} = 15$	$CW_{min} = 15$	$CW_{min} = 15$
STA_3	$CW_{min} = 31$	$CW_{min} = 31$	$CW_{min} = 31$

Table 5.10 Case 2 Parameters

The AIFSN values have been chosen in order to ensure that the QoS condition is always satisfied, i.e. the scheme has been designed as a worst-case scenario. If STA_{G3} were to pick 31, the highest possible value for its BC, STA_{G3} would have to wait for its AIFS plus 31 slots (i.e. 670µs[1]) before transmitting. Whereas if STA_{S1} were to pick 0, the lowest possible value for its BC, STA_{S1} would have to wait for at least its AIFS, i.e. 680µs. This is the same idea as the non-overlapping contention processes scenario described in Figure 5.13. This scenario has also been applied to determine AIFS for the Bronze class. This approach ensures that the QoS condition will always be respected.

The following figure shows the performance characteristics of the wireless STAs in terms of their throughput as a function of the offered load.

[1] See equations 5.1, 5.2 and 5.3

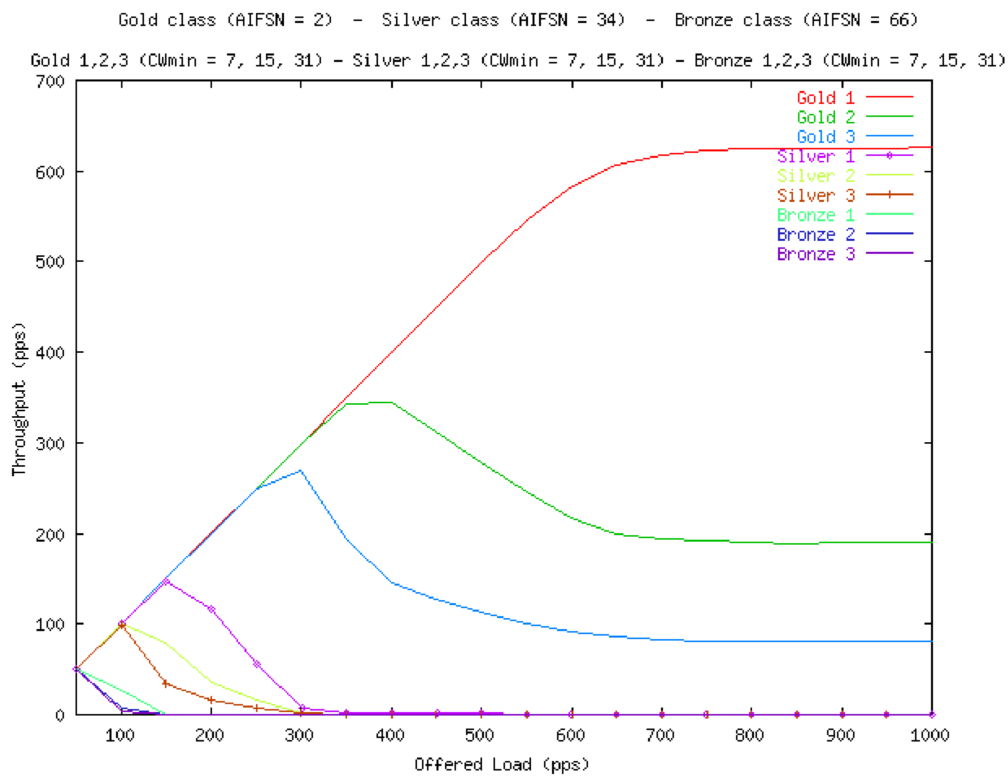

Figure 5.34 Case 2 Throughput

The following figure shows the performance characteristics of the wireless STAs in terms of their PLR as a function of the offered load.

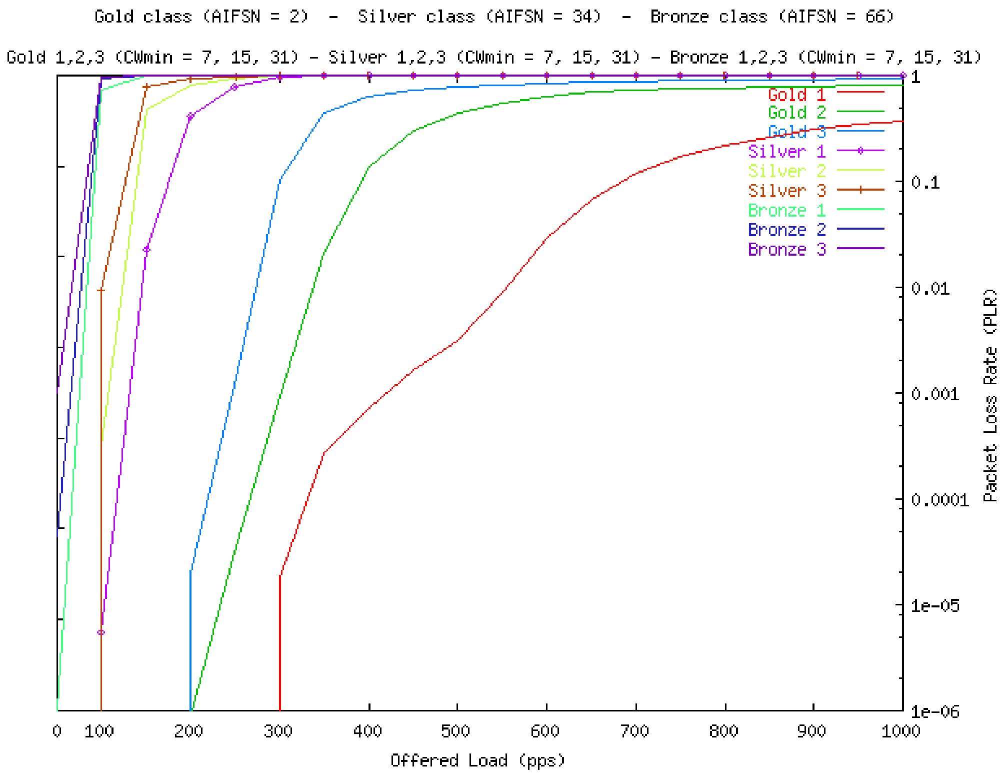

Figure 5.35 Case 2 PLR

We can see from the above figures that the QoS condition is now respected, the Gold STAs always get better service (i.e. in terms of throughput and PLR) than the Silver and Bronze STAs. This is also true for the Silver STAs which also get a better service than the Bronze STAs. It is also important to notice that the priorities within the classes are also respected. Therefore these results confirm that using AIFS to set the class boundaries and CW_{min} to differentiate between the STAs within a class is the better approach.

It should also be noted that this CBDS QoS scheme provides significant improvements for high priority STAs, however these improvements are typically achieved at the cost of reduced performance for lower priority STAs (as one would expect in a differentiated service scheme).

This CBDS QoS scheme could be usefully applied to a real world scenario, e.g. a hotspot service where the operator could offer its customers different levels of services, i.e. Gold, Silver and Bronze. A customer who pays a premium for the Gold service will have the highest priority in terms of receiving service over the other customers using lower (and usually cheaper) services.

5.5 Guidelines for Designing a CBDS QoS Scheme

If this CBDS QoS scheme were to be applied to a larger scale scenario, e.g. a hotspot scenario, the following guidelines should be taken into account.

In a class we can have up to 8 possible different priorities since there are 8 possible values available for the CW_{min} parameter, (i.e. 7, 15, 31, 63, 127, 255, 511 and 1023) otherwise we can have as many STAs with same priorities in a class. The CBDS QoS scheme can also have as many classes of service as needed as there are no limitations with the AIFSN values.

In order to guarantee that all STAs belonging to a higher priority class will always experience a better service than lower priority class STAs, the CBDS QoS scheme should be designed on a worst-case scenario basis, i.e. the boundaries between the classes should be set according to the non-overlapping contention processes scenario as described in Figure 5.13. The following tables summarize all possible AIFSN values that can be used for the Silver and Bronze class boundaries.

The following AIFSN values have been calculated using the equations 5.1, 5.2 and 5.3 with the AIFSN value for the Gold class set to 2.

Gold Priorities (CW_{min} values)	**Silver class (AIFSN values)**
7	10
15	18
31	**34**
63	66
127	130
255	258
511	514
1023	1026

Table 5.11 AIFSN values for the Silver class

Bronze class (AIFSN values):

Silver class / Silver Priorities	10	18	34	66	130	258	514	1026
7	18	26	42	74	138	266	522	1034
15	26	34	50	82	146	274	530	1042
31	42	50	66	98	162	290	546	1058
63	74	82	**98**	130	194	322	578	1090
127	138	146	162	194	258	386	642	1154
255	266	274	290	322	386	514	770	1282
511	522	530	546	578	642	770	1026	1538
1023	1034	1042	1058	1090	1154	1282	1538	2050

Table 5.12 AIFSN values for the Bronze class

Worked example on how to use the tables:

Suppose we have 3 different priorities within the Gold class, i.e. the lowest priority STA will have its CW_{min} set to 31. Therefore the AIFSN value for the Silver class should be set to 34 (see table 5.11) in order to design the CBDS QoS scheme for a worst-case scenario (i.e. the boundaries between the classes should be set such that there are no overlapping contention processes between the STAs belonging to different classes).

Suppose we now have 4 different priorities in the Silver class, i.e. the lowest priority STA will have its CW_{min} set to 63. Therefore the AIFSN value for the Bronze class should be set to 98, i.e. read off from the column "34" which intercept with the row "63" (see table 5.12).

We can see from these tables that if there are too many different priorities in higher priority classes, the AIFSN values for the lower priority classes can reach excessively high values making the CBDS QoS scheme impractical for the lower priority classes. This problem could be resolved by not designing the QoS scheme around a worst-case scenario and therefore smaller values of AIFSN could be used for lower priority classes, but unfortunately this approach would not be able to guarantee that high priority STAs would always get a better service than lower priority STAs.

Consequently this would be a significant problem in the case of a hotspot scenario where a service provider wants to offer many different levels of service to its customers.

A major consideration in designing any such CBDS QoS scheme is that it is traffic load dependent; the performance of a STA depends to a large extent on other STAs traffic loads, i.e. if high priority STAs want to use most of the available bandwidth, lower priority STAs will ultimately suffer. In order to minimise this problem the QoS scheme parameters (i.e. AIFS and CW_{min}) should be updated in a real-time manner based on the number of STAs, STAs priorities, traffic types and network load conditions, etc.

5.6 Summary and Conclusions

From the simulation tests conducted in this study we have identified that when STAs no longer have sufficient BW_{free}, STAs experience poor QoS. It is clear that different STAs (depending on their traffic load) require different amounts of BW_{free} to be available in order to support their QoS requirements. In order to solve this problem we have shown that by varying AIFS or CW_{min} it is possible to control the interaction between the MAC bandwidth components in order to prioritise a particular STA over another and thereby improve its QoS.

We have shown that it is possible to "nail-up" bandwidth for a STA by the appropriate setting of the 802.11e parameters (AIFS and CW_{min}) thereby considerably improving QoS support for STAs or classes of service. We also identified the 802.11e operation region where QoS differentiation through the 802.11e mechanism is effective. We have observed that this region is load dependent which suggests that the 802.11e parameters will have to be continually updated to meet the changing load. It is also obvious from the results that it is easier to differentiate between STAs when combining AIFS and CW_{min} and that CW_{min} is a coarser tuning parameter when differentiating between STAs whereas AIFS appears to be a finer tuning parameter.

By combining the effects of these two 802.11e parameters on QoS provisioning we have devised a set of design rules for establishing a CBDS QoS scheme comprising three QoS classes (e.g. a Gold class, a Silver class and a Bronze class of service). We have shown that AIFS should be used to set the class boundaries and CW_{min} to differentiate between stations within a class. The set of design rules ensures that at all times all STAs belonging to a higher priority class (irrespective of the number of STAs, traffic types, network load conditions, etc.) should always experience a better service than STAs belonging to lower priority classes.

Finally, an additional consideration in any such QoS scheme is that it is traffic load dependent which suggests that if the 802.11e mechanism is to be successfully deployed in a WLAN network (e.g. hotspot scenario) the 802.11e parameters will have to be adjusted in response to the continually changing load conditions.

Chapter 6

Conclusions

6.1 General Conclusions

In this thesis we have reviewed the proposed 802.11e QoS standard that is currently undergoing final revisions by the IEEE for approval sometime in 2004. As 802.11e WLAN equipment is not yet available, performance studies can only be based upon simulation. Consequently we have developed a computer simulation model that faithfully implements the latest draft of the 802.11e standard [7]. The simulator was developed in C/C++ and essentially implements the 802.11e MAC mechanism. We simulated the contention-based channel access EDCA mechanism only and have implemented FIFO buffers in every STA which allowed us to calculate throughput, packet delay, jitter and packet loss which are important QoS metrics when measuring and monitoring the level of QoS experienced by STAs. The simulator was tested using performance results from published papers on the 802.11e standard to ensure correct implementation of the standard by the simulator. After being completely satisfied with the correct operation of the simulator, traffic-engineering tests were carried out with regard to throughput and packet loss. The objective here was to identify the effects of varying the 802.11e parameters on performance. From the range of tuneable parameters that 802.11e offers, we have identified the two most important parameters for QoS provisioning, namely AIFS which is the minimum time interval between the wireless medium becoming idle and the start of transmission of a frame and the CW size from which a random number is drawn as part of the access mechanism.

As a result of these simulation tests a good understanding of the effects of these two parameters on performance was achieved.

In order to gain an insight into the operation of the 802.11e MAC mechanism we have identified a set of MAC bandwidth components that present a useful and intuitive descriptive framework of the MAC mechanism. At any given time the wireless medium can be either busy (STAs are transmitting frames) or idle (the wireless medium is not in use). Based on this observation we define the MAC bandwidth components that describe the MAC operation. First, the load bandwidth (BW_{load}) corresponds to the bandwidth used for frame transmission and which determines the throughput of a STA. Next, the idle bandwidth (BW_{idle}) corresponds to the unused bandwidth on the wireless medium (i.e. when no frames are being transmitted). The BW_{idle} subdivided into two components: The access bandwidth (BW_{access}) which corresponds to the idle bandwidth required by STAs when accessing the medium prior to starting frame transmission and the free bandwidth (BW_{free}) which corresponds to the remaining unused idle bandwidth that will determine the QoS experienced by the STAs.

From the simulation tests conducted in this study we have identified that when STAs no longer have sufficient BW_{free}, STAs experience poor QoS. It is clear that different STAs (depending on their traffic load) require different amounts of BW_{free} to be available in order to support their QoS requirements. In order to solve this problem we have shown that by varying AIFS or CW_{min} it is possible to control the interaction between the MAC bandwidth components in order to prioritise a particular STA over another and thereby improve its QoS.

We have shown that it is possible to "nail-up" bandwidth for a STA by the appropriate setting of the 802.11e parameters (AIFS and CW_{min}) thereby considerably improving QoS support for STAs or classes of service in IEEE 802.11 networks. We also identified the 802.11e operation region where QoS differentiation through the 802.11e mechanism is effective. We have observed that this region is load dependent which suggests that the 802.11e parameters will have to be continually updated to meet the changing load. It is also obvious from the results that it is easier to differentiate between STAs when combining AIFS and CW_{min} and that CW_{min} is a coarser tuning parameter when differentiating between STAs whereas AIFS appears to be a finer tuning parameter.

By combining the effects of these two 802.11e parameters on QoS provisioning we have devised a set of design rules for establishing a class-based differentiated service QoS scheme comprising three QoS classes (e.g. a Gold class, a Silver class and a Bronze class of service). We have shown that AIFS should be used to set the class boundaries and CW_{min} to differentiate between stations within a class. The set of design rules ensures that at all times all STAs belonging to a higher priority class (irrespective of the number of STAs, traffic types, network load conditions, etc.) should always experience a better service than STAs belonging to lower priority classes.

An additional consideration in any such QoS scheme is that it is traffic load dependent which suggests that if the 802.11e mechanism is to be successfully deployed in a WLAN network (e.g. hotspot scenario) the 802.11e parameters will have to be continually adjusted in order to respond to the changing load.

Despite these problems, we find that the proposed 802.11e QoS standard (at least in the case of the EDCA mechanism) to be attractive because of its simplicity and its ability to provide QoS differentiation which is an important improvement over legacy DCF.

6.2 Future Work

In this thesis we have evaluated the EDCA mechanism for contention-based channel access through computer simulation. Future research topics in this area would be to also simulate and evaluate the HCCA polling mechanism for contention-free channel access and to compare performance results with the EDCA mechanism.

Once the proposed 802.11e QoS standard is ratified and equipment becomes available it would be interesting to evaluate the two aspects of the contention-based and contention-free channel access methods in a real wireless LAN and to compare the performance results with the simulated results.

Although 802.11e provides QoS facilities to users it does not in itself deliver QoS. Instead the 802.11e standard should be viewed rather as an enabling technology for QoS provisioning that additionally requires some higher-level control/management functionality. Moreover we have seen that the EDCA mechanism is traffic load dependent, therefore in order for the proposed 802.11e QoS mechanism to be effective, the 802.11e parameters will need to be continually adjusted in order to ensure QoS guarantees are fulfilled for all traffic loads. Consequently it is necessary to develop and implement a Radio Resource Control (RRC) algorithm for automated QoS provisioning on IEEE 802.11e compliant WLANs.

In the following figure we propose a scheme for automated QoS provisioning.

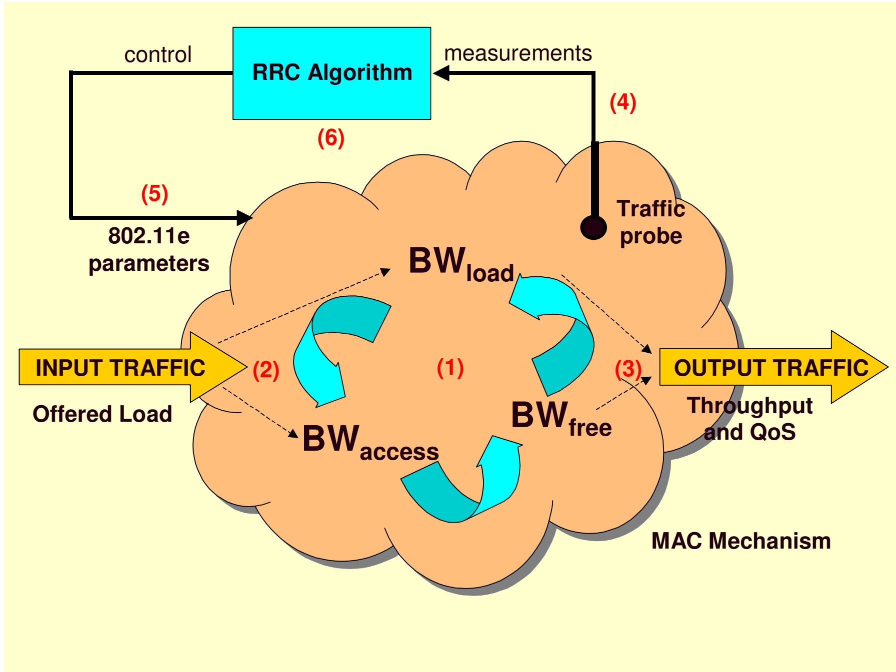

Figure 6.1 Automated QoS Provisioning Scheme

In order to develop the following RRC algorithm a number of key elements need to be taken into consideration.

(1) To determine the nature of the interaction between the various MAC bandwidth components, i.e. BW_{access}, BW_{load} and BW_{free} which to a certain extent have been dealt with in this work.

(2) To establish how the offered traffic load maps onto these MAC bandwidth components.

(3) To establish how the MAC bandwidth components determine the output traffic characteristics, i.e. throughput and associated QoS metrics.

(4) To develop a traffic probe for measuring traffic loads and bandwidth utilisation (i.e. MAC bandwidth components) on the wireless medium. This tool should be non-intrusive and ideally should operate by passively "sniffing" packets on the wireless medium.

(5) To establish how the 802.11e parameters will need to be adjusted in order to deliver QoS provisioning. Again, to a certain extent this has been considered in this work.

(6) Finally to develop a robust and stable RRC algorithm, i.e. closing the control loop whereby the traffic and bandwidth usage information obtained from the probe is used to adaptively adjust the 802.11e parameters.

This work has proven to be an extremely useful study as we have gained an important insight into the operation of the 802.11e MAC. It also suggests a set of design rules for the appropriate setting of the 802.11e parameters in order to establish a class-based differentiated service QoS scheme for deployment in a WLAN hotspot scenario.

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Appendix