Quality of Service Schemes for IEEE 802.11

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MASTER’S THESIS
Quality of Service Schemes for IEEE 802.11
A Simulation Study

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Abstract

This thesis analyzes and compares four different mechanisms for providing QoS in IEEE 802.11 wireless LANs. We have evaluated the Point Coordinator Function (which is the IEEE 802.11 mode for service differentiation), Distributed Fair Scheduling, Blackburst, and a scheme proposed by Deng et al. using the ns-2 simulator. The evaluation covers medium utilization, access delay, and the ability to support a large number of high priority mobile stations. Our simulations show that PCF performs badly, and that Blackburst has the best performance with regard to the above metrics. An advantage with the Deng scheme and Distributed Fair Scheduling is that they are less constrained, with regard to the characteristics of high priority traffic, than Blackburst is.
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Preface

The work of this thesis has been carried out at the Division of Computer Science and Networking at the Department of Computer Science and Electrical Engineering at Luleå University of Technology.

Since we were able to get valuable results in an early stage of this work, we decided to write a conference paper. This paper is going to be presented as a position paper at the Ninth International Workshop on Quality of Service (IWQoS 2001) in the beginning of June 2001.

We are both convinced that the work we have performed during the last eight months have brought us far into the wireless networking area and has prepared us well towards forthcoming employment and studies.

Andreas Almquist
Anders Lindgren

May 2001
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There are a large number of people that have helped us in our work that we would like to thank. We would not have been able to do this without your help. Thank you all!

First we would like to thank our advisor Olov Schelén for all his valuable help and comments and for his encouragement that lead to the conference paper. He has been a great source of inspiration for us and has always been open to discuss ideas and answer questions. Thank you Olov! We would also like to thank all the people at the Division of Computer Science and Communications for providing us with a stimulating and pleasant working environment. Thank you all!

When we have been studying the different methods described in this thesis we have sometimes stumbled upon problems and details that has not been completely clear to us. We would therefore like to thank all the people that have been kind enough to take their time to help us even though they are very busy persons. We would like to thank João Luis Sobrinho for all his help with Blackburst. He has been very helpful both in answering questions and providing us with additional information. Our thanks also go to Matthijs Visser for providing us with a copy of his and M. El Zarki’s paper [1] that we were unable to find elsewhere. Nitin H. Vaidya, Paramvir Bahl and S. Gupta has our deepest gratitude for allowing us to use their ns implementation of the DFS scheme in our evaluations.

I would like give my deepest thanks to my fiancee, Carin, for her enormous support and understanding throughout the last eight months. Without your help, this work would not have been possible for me. Thank you! I would also like to thank my brother Joakim and the rest of my family for their support and insightful thoughts and comments on this work. Thank you!

– Andreas

I would like to thank my parents and my sister for their support and encouragement during my work on this thesis. Thank you for your endless support throughout all my years in school.

– Anders
Chapter 1

Thesis Introduction

1.1 Background

Wireless Local Area Networks (WLANs) are deployed almost everywhere today, mainly because of their enormous flexibility. It is expected that the usage of these networks will increase to cover large areas, such as university campuses, corporate office space, downtown stores, etc. With that, the number of users will increase and almost certainly there will be demands, the same as on wired networks, to be able to run real-time applications such as streaming video and audio. If one tries to extend this to be able to run IP-telephony in these networks there is certainly a need for the network to be able to perform service differentiation between users.

1.2 Goals

The IEEE 802.11 standard is the most widely used WLAN standard today and there is reason to believe that it will remain so because of the wide deployment of IEEE 802.11 compliant devices, and a continuing development of the standard. Therefore, the goal of this thesis was to investigate if there are any schemes proposed today that are capable of delivering service differentiation, Quality of Service, in Wireless LANs and in particular the IEEE 802.11 standard. It is desirable that such schemes are compatible with IEEE 802.11 to allow interoperability with existing devices.

1.3 Research contribution

The main research contribution of this works is that it points out several weaknesses in the IEEE 802.11 standard and that it shows which methods and approaches that could be used to investigate and improve wireless communication/networks further.
1.4 Simulation and Results

The results in this thesis are only to be considered as guidelines to indicate in which direction to go in further research within this area. To be able to draw some real conclusions all these simulations has to be taken one step further, and do some investigations in larger environments where we have node mobility and hand-overs between several base stations.

1.4 Simulation and Results

Our results shows that there already exists several schemes that are able to provide some level of QoS in wireless networks. Each scheme has their own benefits and drawbacks that should be taken into consideration when deploying or further investigating that particular scheme. The results also shows that if you only tries to prioritize some particular kind of traffic, for example IP-telephony (i.e voice), as in Blackburst [2], you are able to perform far better than with a more general approach.

1.5 Document outline

This thesis is organized as follows:

Chapter 1 The thesis introduction gives a short overview over the background, the goals, the research contribution and the results of this thesis. You have probably already read that.

Chapter 2 This chapter discusses and describes the background and techniques behind wireless networks and the simulation environment that we have used to simulate the different QoS schemes.

Chapter 3 This chapter gives a thorough overview over the different QoS schemes that we have studied. It also describes the IEEE 802.11 standard [3] in great detail.

Chapter 4 This chapter describes our simulation setup, what metrics we have looked into and different choices we have made regarding traffic patterns and such.

Chapter 5 This chapter presents the results of our simulations.

Chapter 6 This chapter discusses the results and points out some things worth noting.

Chapter 7 This chapter concludes our work.

Chapter 8 This chapter presents some further research issues and some recommendation on where to take the work presented in the thesis one step further.

Appendix A This appendix contains explanation of the abbreviations used in this thesis.
Chapter 2

Background

2.1 Wireless Networks

The two words wireless and network are commonly used today. Many companies either talks about, have products or present future products that are to be used in a wireless network environment. The concept of wireless networks incorporates several different network technologies, communication ranges and transmission bandwidths. They range from local coverage indoor networks (as IEEE 802.11) to large wide area coverage networks, as the third generation mobile telephony systems (UMTS for example). One common thing about wireless networks is that they suffer from relatively low bandwidth and high bit error rates\(^1\), compared to wired networks. The greatest advantage is that they are very flexible and are easy to deploy.

2.2 Wireless Local Area Networks (WLANs)

In this thesis we have concentrated our work to indoor, or close range networks, which are often called Wireless Local Area Networks. Recently, hardware prices has dropped drastically for infrastructure equipment, and as a result of this, WLANs are deployed almost everywhere. The most common standard for these networks today are the IEEE 802.11 standard \([3]\). There exists other standards such as HiperLan/2 \([4]\), and HomeRF \([5]\) but they are not as widely used.

WLANs usually operates as the license free ISM (Industry, Science and Medical) frequency band at 2.4GHz. HiperLan/2 and the 802.11a extension, among others, are moving towards 5GHz which enables higher transfer rates but decreases the coverage area (narrower transmission range). The transmission bandwidth ranges from 2Mbit/s to approximately 50Mbit/s (HiperLan/2, IEEE 802.11a) and the possible communication distance ranges from

\(^1\)This is the fraction of the data bits that gets altered or corrupted in the transmission between the sender and the receiver.
2.3 IEEE 802.11 - General description

Since this thesis evaluates QoS mechanisms that builds upon IEEE 802.11 we will only give an explanation of the general 802.11 architecture in this chapter. Further details about the medium access mechanism will be presented in chapter 3.

2.3.1 IEEE 802.11 Architecture

Wireless LANs complying to the IEEE 802.11 standard can be used in two modes, ad-hoc mode or infrastructure mode. In an ad-hoc network, stations communicate directly with the stations within transmission range. Stations might cooperate and forward packets for each other so packets can be sent between two stations even if they can not communicate directly. In an infrastructure network, a base station (or access point (AP)) is present and all traffic goes through it, even if its destination is another wireless station within transmission range. A wireless station associates with the closest access point, and uses that to communicate with other wireless stations, and with hosts beyond the wireless network. It is possible for access points to be interconnected in a distribution system (DS) to enable mobile hosts to roam between different access points while remaining in the same IP subnet.

2.3.2 Physical layer radio technologies

Below is a description of different technologies to cope with the physical radio frequency layer (the air). The IEEE 802.11 standard defines transmission over three different physical layers (PHYs): Infrared, Frequency Hopping Spread Spectrum and Direct Sequence Spread Spectrum. The extended 802.11a (and HiperLan/2) uses a physical layer called Orthogonal Frequency Division Multiplexing which operates at the 5GHz band. The infrared PHY requires free sight between the communicating nodes and thus is not to be expected to be used in any large scale network, but rather in small conference rooms and in direct communication between two nodes. We will therefore only describe the three radio spectrum technologies here.

Frequency Hopping (FH) Spread Spectrum

Frequency hopping is used in many radio applications due to the inherent robustness against interference and jamming. The frequency hopping transmission method transmits and receives on one frequency for a short time and then jumps to another frequency. IEEE 802.11 does 1 MHz jumps once every tenth of a second. The jumping pattern is usually based on some pseudo-random hopping algorithm. Since the hopping is performed several times per second that makes it very difficult for an intruder to "listen" to the transmission. To be able to do so he needs to know exactly when in time the particular node is going to change frequency and he needs to know the hopping sequence.
Within the ISM frequency band there are 78 frequencies available for IEEE 802.11 and since each base station has its own hopping sequence it basically creates its own LAN segment. Theoretically this means that 78 LAN segments are able to have ongoing transmissions at the same time in the same coverage area. Fig. 2.1 shows an example of this.

Using FH therefore provides great scalability, since several base stations could be located in the same coverage area, creating numerous wireless LAN segments in this area, which increases the supported number of users in that area. To increase the overall throughput in the coverage area it could be possible to do load balancing between the different base stations. One drawback with FH is that the maximum bandwidth is specified at 1 MHz which leads to a transmission data rate of only either 1 or 2 Mbit/s.

**Direct Sequence Spread Spectrum**

Direct Sequence Spread Spectrum (DSSS) is the transmission technique used by both the ordinary 802.11 and the extension 802.11b, were the later supports transfer rates up to 11 Mbit/s. DSSS works such that the original data stream is XOR-ed with a spreading factor or "chipping code". The result of this is that the original data bit is broken into multiple "sub-bits" or chips, as shown in Fig. 2.2. Each chip is represented by a 1 or a 0. All these chips are transmitted over a much broader frequency range than the "normal" data stream, as illustrated in Fig. 2.3. A receiver (with the same chipping code "key") then takes all the transmitted chips and runs them through a decoder to reassemble the original data stream.

As the signal is spread over the transmission band and as the chipping introduces a sort of encryption of the data this ensures a greater degree of security. An intruder would first have to figure out which range of the frequency band that was used for the transmission and then figure out the chipping code. As the amplitude in the transmission in DSSS is very small (Fig. 2.3) the transmission actually looks like noise in the radio spectrum, which makes it
even more difficult to intercept a transmission.

Since the signal is spread over several frequencies this provides some sort of immunity towards jamming. A typical interference source, as a microwave oven, would only jam a small portion of the frequency band. Even though some of the chips are corrupted, the signal will be able to be recovered due to the chipping and encoding.

In IEEE 802.11 there are 11 channels (frequency ranges) available for DSSS, but only three of them are non-overlapping as depicted in Fig. 2.4. This means that in a 802.11 network, which uses this technique, there can only be three base stations that have overlapping coverage areas. The implications, if this is not taken into the calculations when deploying a network, will be high bit-error rates, which yields greater packet losses which ends up in lower data transfer rates (throughput).

In contrast to FH (described above), DSSS supports greater data transfer rates, at the cost of scalability. If the density of users in the planned coverage area is expected to be high (as in lecture halls, conference rooms or shopping streets) FH is likely to be a better solution/choice.
Orthogonal Frequency Division Multiplexing (OFDM)

This is the technique used by both HiperLan/2 and IEEE 802.11a at the 5GHz frequency band. The basic idea is to make a broadband, high data rate transmission, as in DSSS (described above). But in OFDM the data is divided into several interleaved parallel bit streams where each stream modulates a separate sub carrier. By modulating the channel in this way the channel frequency is divided into several independent sub channels.

One of the great benefits with OFDM is that it uses the radio spectrum efficiently since the sub channels could be packed close together. One drawback is that due to the high frequency band (5GHz) the transmission range is rather small (30 to 150m only).

2.4 The hidden node problem

The hidden node problem is one of the most common problems in wireless networks (besides the high bit-error rates). This problem comes from that every wireless node has limited radio transmitting range and that every wireless node can thus not be expected to be able to communicate with every other node in the network. The phenomenon is easiest explained with the following example (depicted in figure 2.5).

Consider a WLAN consisting of three nodes, where node A and C only are able to communicate with node B and not with each other. If node A has an ongoing transmission with B, this could easily be interrupted by a transmission from C to B, since C cannot hear the the transmission form A. One could say that node C is hidden from node A.

IEEE 802.11 provides a solution to this by using a “Request To Send - Clear To Send” (RTS/CTS) scheme. In the RTS-CTS negotiation algorithm the node who wants to send data...
sends a RTS frame to the destination node which responds with a CTS frame if the medium is idle. Upon reception of the CTS frame, the first station transmits its data frame, and if a CTS is not received, it tries again at a later time. The RTS and CTS frames contain the duration of the coming data transmission, which allows stations overhearing the RTS/CTS exchange to refrain from transmitting during this time. To further explain this, consider the scenario in Fig. 2.5. Here, any transmission between A and B could be interrupted by a sudden transmission from C to B. Using the RTS-CTS scheme here would eliminate such interruptions since C will be able to hear the CTS response from B and thus knows how long B will be busy in a transmission with A.

This reduces the probability for collisions but introduces a lot of packet overhead. Therefore it is recommended to only use this for data frames larger than some threshold. This since it costs even more if a large frame is corrupted due to a collision. This problem is addressed further by G. Anastasi et al. [6] who also presents some general recommendations.

2.5 NS - Network Simulator

Ns [7] is one of the most commonly used simulators today, in the networking research community, mostly because of its open-source. The simulator is a discrete event simulator originally developed at LBL (Lawrence Berkeley Laboratory) at University of Berkeley, within the VINT (Virtual InterNetwork Testbed) project. The main reason why this simulator has been frequently used is that it has substantial support, and accurate implementations, for TCP as well as other transport protocols over conventional wired networks. Because of its good TCP implementations it has often been used to simulate and evaluate TCP performance.

Berkeley released the initial code that made wireless network simulations possible in ns. That code provided some support to model wireless LANs, but was fairly limited. As a result of the Monarch project at Carnegie Mellon University [8] the simulator was extended with support for node mobility, a realistic physical layer, radio network interfaces and an imple-
2. Background

2.5 NS - Network Simulator

mentation of the IEEE 802.11 DCF MAC protocol. This work was presented as a part of a larger study of performance for different ad-hoc routing protocols [9]. It was this contribution that made it possible to perform real wireless simulations with ns.

2.5.1 Simulator internals

The simulator is written in C++ and it uses OTcl as a command and configuration interface [10]. This means that OTcl scripts are used to set up simulation scenarios in the simulator. One great benefit of this is that there is no need to recompile the simulator between different simulations since you are able to set up topology, link bandwidth, traffic sources, etc. from the OTcl scripts. So, once you have implemented the basic functionality within the simulator (C++ code) you only have to change the OTcl scripts to run various simulations.
Chapter 3

Overview

In this chapter we describe the QoS mechanisms evaluated in Chapter 5. For all details we refer to the papers [3, 11, 12, 2, 13] where the schemes were proposed.

3.1 IEEE 802.11

The IEEE 802.11 standard [3] for wireless Local Area Networks (WLANs) is the major standard for WLANs today. IEEE 802.11 has two different access methods, the mandatory Distributed Coordinator Function (DCF) and the optional Point Coordinator Function (PCF). The latter aims to support real-time traffic by allocating specific time slots for the real-time data.

3.1.1 Distributed Coordinator Function

The Distributed Coordinator Function is the basic access mechanism of IEEE 802.11. It uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm to mediate the access to the shared medium. When the MAC layer gets some data that should be transmitted, it senses the medium for a DCF interframe space (DIFS) period of time, the frame is transmitted. Otherwise, a backoff time $B$ (measured in time slots) is chosen randomly in the interval $[0, CW)$, where $CW$ is the so-called Contention Window. After the medium has been detected idle for at least a DIFS, the backoff timer is decremented by one for each time slot the medium remains idle. When the backoff timer reaches zero, the frame is transmitted. If the frame is successfully received at the destination, an acknowledgement frame (ACK) is sent to the sender. Upon detection of a collision (which is detected by the absence of an acknowledgement frame), the contention window is doubled according to (3.1), where $i$ is

---

An interframe space, IFS, is the time a station waits when the medium is idle before attempting to access it. IEEE 802.11 defines several IFSs, and by using shorter IFS, the medium is accessed prior to stations using a longer IFS. This is e.g. used to ensure that an acknowledgment frame is sent before any other station can send data. The relations between different IFSs can be found in Fig. 3.1.
3.1 IEEE 802.11

3.1 Overview

The number of attempts (including the current one) to transmit the frame that has been done, and \(k\) is a constant defining the minimum contention window, \(CW_{min}\). A new backoff time is then chosen and the backoff procedure starts over. Since the contention window is doubled for every collision the probability that the two colliding nodes will choose the same backoff time decreases. The backoff mechanism is also used after a successful transmission before sending the next frame and thus also reducing the probability for collisions. After a successful transmission, the contention window is reset to \(CW_{min}\).

\[
CW_i = 2^{k+i-1} - 1
\] (3.1)

3.1.2 Point Coordinator Function

PCF is a centralized, polling-based access mechanism which requires the presence of a base station that acts as Point Coordinator (PC). If PCF is supported, both PCF and DCF coexist and in this case, time is divided into superframes as shown in Fig. 3.2. Each superframe consists of a contention period where DCF is used, and a contention free period (CFP) where PCF is used. The CFP is started by a special frame (a beacon) sent by the base station. Since the beacon is sent using ordinary DCF access method, the base station has to contend for the medium, and therefore the CFP may be shortened.
The PC keeps a list of mobile stations that have requested to be polled to send data. During the CFP, it sends poll frames to the stations when they are clear to access the medium. To ensure that no DCF stations are able to interrupt this mode of operation, the IFS between PCF data frames is shorter than the usual DIFS. This space is called a PCF interframe space (PIFS). To prevent starvation of stations that are not allowed to send during the CFP, there must always be room for at least one maximum length frame to be sent during the contention period.

### 3.2 Deng

Deng and Chang proposes a different method to support station priorities that requires minimal modifications of the IEEE 802.11 DCF MAC protocol \[11\]. Since this scheme doesn’t have any real name, we will refer to it as the Deng scheme from the name of one of the authors.

The Deng scheme uses two properties of IEEE 802.11 to provide differentiation: the interframe space (IFS) used between data frames, and the backoff mechanism. If two stations use different IFS, a station with shorter IFS will get higher priority than a station 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 PCF, these can be used for easy implementation of the Deng scheme. By using these two different interframe spaces, traffic can be differentiated and classified into two classes. To further extend the number of available classes, the backoff mechanism could be used to differentiate between stations. This is done by designing the backoff algorithm such that it generates backoff intervals in different intervals, depending on the priority of the station.

Table 3.1 shows four different priority classes (0-3) defined using two different interframe spaces, and two different backoff algorithms \[11\]. The backoff algorithms chosen guarantees that stations that uses the low priority backoff algorithm always generates longer backoff intervals than stations with higher priority.

<table>
<thead>
<tr>
<th>Priority</th>
<th>IFS</th>
<th>Backoff algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>DIFS</td>
<td>(B = \frac{2^{2+i}}{2} + \left\lfloor \rho \times \frac{2^{2+i}}{2} \right\rfloor)</td>
</tr>
<tr>
<td>1</td>
<td>DIFS</td>
<td>(B = \left\lfloor \rho \times \frac{2^{2+i}}{2} \right\rfloor)</td>
</tr>
<tr>
<td>2</td>
<td>PIFS</td>
<td>(B = \frac{2^{2+i}}{2} + \left\lfloor \rho \times \frac{2^{2+i}}{2} \right\rfloor)</td>
</tr>
<tr>
<td>3</td>
<td>PIFS</td>
<td>(B = \left\lfloor \rho \times \frac{2^{2+i}}{2} \right\rfloor)</td>
</tr>
</tbody>
</table>
3.3 Distributed Fair Scheduling

There exist several fair queuing schemes that provide fair allocation of bandwidth between different flows on a node [14, 15]. In this context, fair means that each flow gets bandwidth proportional to some weight that has been assigned to it. These schemes are centralized in the sense that they run on a single node which has access to all information about all the flows. Since different weights can be assigned to the flows, this can be used for differentiation between flows.

N. H. Vaidya et al. has presented an access scheme which utilizes the ideas behind fair queuing in the wireless domain [12]. This access scheme is called the Distributed Fair Scheduling (DFS) algorithm.

The Distributed Fair Scheduling scheme is based on the fair queuing mechanism known as Self-Clocked Fair Queuing (SCFQ) [14], and uses the backoff mechanism of IEEE 802.11 to determine which station should send first. Before transmitting a frame, the backoff process is always initiated, even if no previous frame has been transmitted. The backoff interval is calculated as shown in (3.2), where size(pkt) is the size of the packet to send, \( \phi \) is the weight of the station, \( \rho \) is a random variable with mean 1, and Scaling Factor is used to scale the backoff intervals to values of suitable magnitude. Since the backoff interval will be longer the lower the weight of the sending station is, differentiation will be achieved. Further, fairness is achieved by using the size of the packet to be sent in the calculation of the backoff interval. This will cause larger packets to get longer backoff intervals than small packet, allowing a station with small packets to send more often so that the same amount of data is sent.

\[
B = \left( \rho \times \left[ \text{Scaling Factor} \times \frac{\text{pktsize}}{\phi} \right] \right)^{3.2}
\]

If a collision occurs, a new backoff interval is calculated using the backoff algorithm of the IEEE 802.11 standard where the contention window is given by (3.1).

As can be noted from (3.2), the backoff intervals of DFS are inversely proportional to the weight of a flow. This can cause the backoff intervals to be unnecessarily long when the weights of backlogged flows are small. Therefore, an exponential mapping scheme has been proposed that compresses the backoff interval above some threshold [12].

3.4 Blackburst

As an attempt to improve performance of real time streams, Sobrinho and Krishnakumar has proposed a scheme called Blackburst [2], and later some enhancements to that scheme [13]. The main goal of Blackburst is to minimize the delay for real time traffic, and it is somewhat different from the other schemes since it imposes certain requirements on the traffic to be prioritized. Blackburst requires that all high priority stations try to access the medium with constant intervals, \( t_{sch} \) (this interval has to be the same for all high priority stations). Further, Blackburst also requires the ability to jam the wireless medium for a period of time.

\(^2\)A flow is considered backlogged when it constantly has queued packets.
When a Blackburst station wants to send a frame, it senses the medium to see if it has been idle for a PIFS and then sends its frame. On the other hand, if the medium is found busy, the station waits until it has been idle for a PIFS and then enters a black burst contention period. The station now sends a so-called black burst by jamming the channel for a period of time. The length of the black burst is determined by the time the station has been waiting to access the medium, and is calculated as a number of black slots. After transmitting the black burst, the station listens to the medium for a short period of time (less than a black slot) to see if some other station is sending a longer black burst. That would imply that the other station has waited longer and thus should access the medium first. If the medium is idle, the station will send its frame, otherwise it will wait until the medium becomes idle again and enter another black burst contention period. By using slotted time, and imposing a minimum frame size on real-time frames, it can be guaranteed that each black burst contention period will yield a unique winner [2].

After the successful transmission of a frame, the station schedules the next access instant (when the station will try to transmit the next frame) $t_{sch}$ seconds in the future. This has the nice effect that real-time flows will synchronize, and share the medium in a TDM$^3$ fashion [2]. This means that unless some low priority traffic comes and disturbs the order, very little blackbursting will have to be done once the stations have synchronized.

---

$^3$Time Division Multiplexing
Chapter 4

Simulations

To evaluate the methods described in section 3, we used the network simulator *ns-2* [7, 10] which already has IEEE 802.11 DCF functionality. We extended the simulator by implementing IEEE 802.11 PCF and the other schemes\(^1\), and ran the simulation scenarios described below to measure three different metrics: throughput, access delay and maximum number of high priority stations.

4.1 Scenarios

In our simulations, the wireless topology consisted of several wireless stations and one base station in the wireless LAN. The base station was connected to a wired node (H in Fig. 4.1) which serves as a sink for the flows from the wireless domain. The parameters for the wired link were chosen to ensure that the bandwidth bottleneck of the system is within the wireless LAN. All wireless stations are located such that every station is able to detect a transmission from any other station, and there is no mobility in the system. This means our results will not be impacted by mobility and phenomenon such as the hidden node problem (see section 2.4).

We have used two kinds of traffic in our simulations. For the first The traffic in our simulations was generated by each station sending 230 byte frames (including IP and UDP headers) to H at constant intervals. The interval between frames was varied between simulations to vary the load. The load of the system has been calculated according to (4.1), where \(n_{\text{stations}}\) is the number of mobile stations, \(\text{size}_{\text{pkt}}\) is the size of the packets sent, \(\text{interval}_{\text{pkt}}\) is the interval between the packets, and \(c_{\text{bitrate}}\) is the channel bit-rate.

\[
\text{load} = \frac{n_{\text{stations}} \cdot \text{size}_{\text{pkt}}}{c_{\text{bitrate}} \cdot \text{interval}_{\text{pkt}}} \quad (4.1)
\]

Each point in our plots is an average over ten simulation runs, and the error bars indicate

\(^1\)except DFS, which the authors proposing DFS had the benevolence of providing us with their ns implementation of DFS
4.2 Metrics

Choosing the correct metrics to use in the evaluation of the QoS mechanisms is vital to the result and validity of the evaluation. The metrics we have used are throughput, access delay, and maximum number of high priority stations.

4.2.1 Throughput

We have looked at both the average throughput for the stations at each priority level, and the total throughput for all stations together. The throughput for different priority levels shows how well the QoS schemes can provide service differentiation between the various priority levels. The total throughput of all stations shows the utilization of the wireless medium. Wireless bandwidth is a scarce resource, so efficient use of it is vital.

To be able to compare the graphs from different levels of load, we have chosen to plot a normalized throughput on the y axis, rather than the absolute throughput. The normalized throughput is calculated as the fraction of the offered data that is actually delivered to the destination.
4. Simulations

4.2.2 Average access delay

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

4.2.3 Maximum number of high priority stations

To be able to determine to what extent the schemes were able to provide good service to the high priority traffic, we ran simulations where the stations sent 230 byte frames with an interframe interval of 28 ms. This corresponds to a bit rate close to 64 kbit/s, which is a common bit rate for sampled voice. We fixed the low priority traffic load at certain levels by using different numbers of low priority stations. We then increased the number of high priority stations to see how many high priority stations that could get good service. We used two definitions of good service. The first, which considers throughput, requires that 95% of the offered data is delivered. The second requires the average access delay to be below 20 ms.

4.3 Method specific details

This section describes the simulation details that are specific to the different QoS mechanisms. Table 4.1 shows the parameter values used in our simulations. Unless otherwise specified, we have used the parameter values defined in the IEEE 802.11 standard, and in the papers that proposed the other schemes [3, 2, 11, 12].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time slot</td>
<td>20 µs</td>
<td>DIFS</td>
<td>50 µs</td>
</tr>
<tr>
<td>PIFS</td>
<td>30 µs</td>
<td>High prio</td>
<td>3</td>
</tr>
<tr>
<td>Superframe</td>
<td>110 TU²</td>
<td>Low prio</td>
<td>1</td>
</tr>
<tr>
<td>bitrate</td>
<td>2 Mbit/s</td>
<td>DFS</td>
<td>100 µs</td>
</tr>
<tr>
<td>size pkt</td>
<td>230 bytes</td>
<td>High weight</td>
<td>0.075</td>
</tr>
<tr>
<td>CWmin</td>
<td>3</td>
<td>Low weight</td>
<td>0.025</td>
</tr>
<tr>
<td>Blackburst</td>
<td></td>
<td>Scaling factor</td>
<td>0.02</td>
</tr>
<tr>
<td>Black slot</td>
<td>20 µs</td>
<td>CWmin</td>
<td>3</td>
</tr>
</tbody>
</table>

²¹ TU = 1024 µs
4.3 Method specific details

4.3.1 IEEE 802.11 (PCF)

During a CFP the Point Coordinator (the base station) polls the stations in its polling list in a round robin fashion. If all stations have been polled once, the CFP will be ended prematurely. If there is not enough time to poll all stations the next station in the list will be polled first in the next CFP.

4.3.2 Deng

The Deng scheme allows us to have four different priority levels, but to be able to perform comparisons with the other schemes, we only wanted to have two priority levels in our simulations. We have done simulations with all possible combinations of priority levels. We have chosen to present the results when using priority 3 for high priority traffic, and priority 1 for low priority traffic (see table 3.1 for details on the different priorities). This combination gives a good differentiation without causing low priority traffic to suffer too much from starvation.

4.3.3 DFS

Since DFS allows arbitrary weights to be assigned to the flows, many different priority levels can be used. For the same reason as with the Deng scheme, we only wanted to have two levels of priority in our simulations. Therefore we assigned the high priority stations weights of 0.075, and the low priority stations weights of 0.025. The reason for this is that the authors try to keep the sum of all weights close to 1, see [12]. Our choice of weights will make the sum of the weight vary from 0.5 to 1.5 as the number of high priority stations varies (when using a total of 20 stations), which we believe is reasonable. To enhance the performance when there is much low priority traffic, we decided to use the exponential mapping of the backoff intervals.

4.3.4 Blackburst

Two different modes of operation of blackburst, with and without feedback from the MAC layer to the application, are presented [13]. Using feedback would probably have yielded a better result, but that requires special, Blackburst-aware applications. Therefore we decided to use the mode without feedback in our simulation to make the results comparable with the results from the other methods.
Chapter 5

Results

5.1 Throughput

Our first simulations compared the performance of the QoS schemes with regard to throughput and access delay when varying the fraction of high priority traffic. Fig. 5.1 shows the normalized throughput versus the fraction high priority stations for the different QoS schemes at different loads. The graphs labeled “PCF/DENG/DFS/BB High” show the average normalized throughput for all high priority stations using the corresponding scheme, and conversely for graphs labeled “PCF/DENG/DFS/BB Low”. These naming conventions also hold for Fig. 5.3, and analogous naming has been used in Fig. 5.2 and 5.4. Fig. 5.2 shows the total throughput, which indicates how well the different schemes utilizes the medium.

The first observation we made was that even at low loads, such as 0.46, when using PCF, low priority flows get significantly lower throughput compared to the other schemes. The high priority stations perform acceptable at this low load, but the performance for these starts to deteriorate when the amount of high priority traffic increases.

When the load was increased to 0.541, we found that for all schemes, high priority stations are able to send all their data up until a certain percentage of high priority traffic. After that the performance starts to degrade for all schemes except Blackburst. Among the other schemes, PCF is the first to lose performance, while Deng and DFS last a while longer and also have much better performance for low priority traffic.

When the load was increased even more, up to 0.657, we noted that not even Blackburst is capable of delivering all data of the high priority stations, when there are only Blackburst stations. It should be duly noted that DFS gives better performance to low priority stations than Deng even though the two schemes give almost the same result for the high priority traffic. This implies that DFS will utilize the medium more efficiently, which also can be seen in Fig. 5.2.

Finally, we applied really high load (0.968) to the system, which caused some of the schemes to perform inferiorly. Blackburst once again was the scheme that could give the best service to high priority stations. One thing that certainly should be noted here is the
low priority traffic. The Deng scheme gives extremely low throughput to low priority flows, which almost leads to complete starvation. Blackburst takes this one step further and causes complete starvation of low priority traffic. The PCF and DFS schemes do not starve the low priority traffic to that extent (with DFS giving better performance among those two), at the expense of that the high priority traffic receive worse service than with Blackburst and the Deng scheme.

As shown in Fig. 5.2, at all levels of load, Blackburst utilizes the medium most efficiently (highest total throughput). The total throughput for Deng and DFS are similar to each other, but higher than for PCF which has the worst medium utilization.

One interesting observation is that the throughput for low priority traffic in the PCF and Deng cases increases slightly when there is only one low priority station. Our hypothesis about this is that all high priority stations will send their frames in what appears to the low priority stations as a big “chunk” (with PCF they send their frames during the CFP, with Deng the stations will send after each other if all high priority stations have frames to send and are not in a backoff process since they use a shorter IFS than low priority stations). After sending their frames, all high priority stations will start decrementing their backoff timers at approximately the same time and therefore will the medium be idle for a while. During this time, low priority stations will be able to access the medium. If there are more than one low priority station wishing to send a frame they will have to contend for the medium. On the other hand, if there is only one low priority station in the system, it won’t have to contend for the medium at this time and will therefore be able to send its frame. Thus it seems reasonable that there is a slight increase in performance when there is only one low priority station. A similar phenomenon occurs for Blackburst at a load of 0.541 where the performance of low priority stations increased when the fraction of high priority traffic increased. Since increasing the amount of high priority traffic also implies decreasing the amount of low priority traffic, there will be less stations contending for access to the medium using CSMA/CA, but the medium idle time will not decrease as much since Blackburst stations will synchronize themselves [2].

5.2 Access delay

In the investigation of the second metric, access delay, it was found that Blackburst and Deng performs well for high priority traffic. The plots in Fig. 5.3 shows the average access delay for different priority levels for the QoS schemes. As shown in the plots, the DFS and PCF simulations give similar results at all levels of load, even though DFS performs slightly better at low loads. At low load, all the schemes except PCF have rather constant delays within the priority levels that does not depend on the percentage of high priority traffic. Notably, Blackburst also gives very low delay to low priority traffic.

At a load of 0.541, it is clear that when the fraction of high priority traffic grows larger, the access delay starts to increase for all schemes except Blackburst. As we saw earlier when looking at the throughput, using Blackburst, the performance of the low priority stations actually improves when increasing the amount of high priority traffic. The delay for the Deng low priority traffic starts to become rather high with 0.541 load, and increases rapidly as the load is increased to 0.657. The high priority traffic using Deng does however gain from
5. Results

5.3 Maximum number of high priority stations

This since it keeps a rather low delay even with increased load. Nevertheless, high priority stations using Blackburst get even lower access delay, without incurring equal amount of “punishment” on the low priority traffic.

When the load is increased to a very high level (0.968), the delay of low priority traffic with Blackburst increases very rapidly when the amount of high priority traffic exceeds some threshold. One might remember that at this high load, low priority traffic was completely starved when there were much high priority traffic.

5.3 Maximum number of high priority stations

The investigation of the third metric, maximum number of high priority stations, indicates that Blackburst is the scheme capable of supporting the largest number of high priority stations with good service, independent of the amount and characteristics of low priority traffic.

Figure 5.4: Maximum number of high priority stations that can send at least 95% of the offered traffic for various levels of offered low priority traffic load.
5.3 Maximum number of high priority stations

In Fig. 5.4 we plot the maximum number of high priority stations that receive good performance, regarding throughput, for varying levels of offered low priority load. From these it can be noted that Deng, as well as Blackburst, performs reasonably well and is not affected much by the low priority load. On the other hand, PCF and DFS are not able to handle a large number of high priority stations when the amount of low priority traffic increases. In the case of DFS, this is due to the fact that DFS does not try to give the higher priority really good service at all costs, but tries to distribute the bandwidth fairly among the stations according to their weights.

When investigating this metric with regard to access delay we get similar results, as shown in Fig. 5.5. One thing worth noting is that Deng is able to handle more high priority stations in this case, which indicates that Deng is better at providing low delay than high throughput, and might be a suitable alternative if low access delay for high priority traffic is vital.

Figure 5.5: Maximum number of high priority stations with average access delay of at most 20 ms for various levels of offered low priority traffic load.
Figure 5.1: Average throughput for a station at the given priority level.

5.3 Maximum number of high priority stations
Figure 5.2: Total throughput for the QoS schemes.

5.3 Maximum number of high priority stations

5. Results
5. Results

5.3 Maximum number of high priority stations

Figure 5.3: Average delay for a station at each priority level.

- Offered load 0.46
- Offered load 0.541
- Offered load 0.657
- Offered load 0.968
Chapter 6

Discussion

In this thesis we have shown that all the evaluated schemes are able to provide service differentiation to some extent. However, we have also seen that there is a limit on the number of high priority stations that can be given good service at the same time. Thus, it would be desirable to be able to perform admission control when a new station or flow wishes to use the higher priority class. One major advantage that PCF has over the other schemes is that implementation of admission control would be rather simple [16]. Since PCF is centralized, the base station has knowledge of the available resources and can decide whether to admit another flow or not. Because of the distributed nature of the other schemes, admission control and service enforcement are harder to realize for those schemes. However, recent work presented by M. Barry et.al. [17] shows some interesting schemes for distributed admission control.

In a real life scenario, it is reasonable to believe that not all stations transmit the same kind of traffic. It is especially likely that low priority traffic won’t have constant bit rate, but rather be some other type of traffic. Therefore, we also ran simulations where the background (low priority) traffic was ON-OFF sources where the ON and OFF periods came from a Pareto distribution. This results in a much burstier low priority traffic, but that did not affect the high priority traffic in any significant way. We have not studied the effect different packet sizes would have on the schemes, but we believe that the impact of that would be rather small. Thus, we feel that the results presented here would be valid even if the low priority traffic has different properties than in our simulations.

One thing that might be problematic for Blackburst is that it requires high priority traffic to access the medium at constant intervals, which should be the same for all high priority traffic. However, one possible scenario where Blackburst certainly would provide great benefits would be if for example a company would wish to run telephony over the corporate WLAN. Then all the users using the WLAN for telephony would have the same kind of traffic, and all the users using the WLAN for ordinary data transfer would use the low priority (which in the Blackburst case is just normal IEEE 802.11 DCF, meaning that no special precautions have to be taken by those users). In such a scenario, it is likely that special purpose real time applications are used (e.g. implemented in hardware in a phone). This opens the possibility
6. Discussion

to use the Blackburst mode with feedback to the application, probably yielding even better results than those presented in this thesis.
Chapter 7

Conclusions

From our simulations we can conclude that the PCF mode of the IEEE 802.11 standard performs poorly compared to the other schemes evaluated. A reason for this is the fact that PCF is centralized (which also requires the presence of a base station), forcing it to utilize control frames to mediate access to the medium. This overhead wastes bandwidth that could have been used for data transmissions.

Our simulations show that Blackburst gives the best performance to high priority traffic both with regard to throughput and access delay. At low loads, it also gives rather good performance to low priority traffic, but it does however deteriorate to complete starvation of low priority traffic at very high loads. A drawback with Blackburst is the requirements it imposes on the high priority traffic.

If the traffic requirements of Blackburst can not be met, Deng might be a suitable alternative. Although not being able to provide as good service as Blackburst, it still can serve quite many high priority stations and give very low delay to high priority traffic.

Both Blackburst and Deng starves low priority traffic at high loads of high priority traffic. In many cases this is not desirable, and one would rather want a relative differentiation. Then DFS would do a very good job. It always gives better service to the high priority traffic, and still does not starve the low priority traffic, but ensures that it gets its fair share of the bandwidth.

Further, our simulations show that Blackburst is the scheme that gives the best medium utilization. This is important, given the scarcity of bandwidth in wireless networks. We can also see that the access method of the IEEE 802.11 standard is the method that gives the worst utilization of the medium. This conclusion was expected from the results from M. A. Visser et.al. [1]
7. Conclusions
Chapter 8

Future Work

In this thesis we have evaluated the QoS mechanisms described in chapter 3 by simulation. One thing that would be interesting to do in the future is an authentic evaluation of the mechanisms in a real wireless LAN. Since this evaluation does not consider node mobility and roaming between several base stations these are aspects that needs to be investigated and simulated further.

Another aspect that needs to be studied is admission control. To be able to provide service differentiation that gives certain guarantees to high priority traffic, it does not suffice to just have a QoS aware access mechanism. If no admission control is used, it is very likely that too many users will use the higher priority class. This results in an overload that can’t be handled, thus reducing the performance of high priority stations.

The traffic used in our simulations (constant bit-rate traffic), is not very realistic. Simulations should be done with more realistic traffic patterns to be able to determine the behaviour of the schemes in real life.

The IEEE 802.11 working group is currently working on an extension to the IEEE 802.11 standard that will provide support for service differentiation. It would be interesting to evaluate the schemes of this new extension and see how they perform compared to the schemes evaluated in this thesis.
8. Future Work
Appendix A

Glossary

CFP  Contention Free Period
CSMA/CA  Carrier Sense Multiple Access with Collision Avoidance
CW  Contention Window - Used by IEEE 802.11 DCF to calculate the backoff interval.
DCF  Distributed Coordinator Function - The basic access mechanism of IEEE 802.11.
DFS  Distributed Fair Scheduling
DIFS  Distributed interframe space
Frame  Data transmission unit in the MAC layer. Consists of a Header and the data from upper layers.
IEEE  The Institute of Electrical and Electronics Engineers
IEEE 802.11  Standard for wireless LANs. Specifies medium access control (MAC) and physical (PHY) layers.
IFS  Interframe space
ISM  Industry, Science, Medical frequency band.
MAC  Medium Access Control
PC  Point Coordinator
PCF  Point Coordinator Function - Centralized, polling based access mechanism of IEEE 802.11 to support service differentiation.
PHY  Physical layer
PIFS  Priority interframe space
A. Glossary

**QoS** Quality of Service

**TDM** Time Division Multiplexing

**WLAN** Wireless Local Area Network
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