A contention window differentiation mechanism for providing QoS to high priority data in 802.11

Technical Report

by

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Abstract

IEEE 802.11 based wireless LANs (WLAN) are rapidly replacing traditional wireline ethernet LANs. Running real time voice and video applications over LANs is becoming common place. These applications require QoS in terms of delay, throughput etc. But 802.11 does not have inherent QoS support. Since 802.11 has a large installation base and QoS-aware IEEE 802.11e standard based products are not available yet, providing QoS in 802.11 WLANs is an important issue. In this paper, we propose a MAC protocol based on 802.11 which can provide QoS to real time applications. The MAC assigns different contention window to two priority classes to provide service differentiation. When collision occurs, contention window is increased in a linear fashion and the new contention windows for high and low priority traffic become non-contiguous. This unique method of contention window management provides better relative performance between the two classes and achieves higher system throughput. We propose two modes of realizing this new MAC protocol, present an analytical model to show that high priority class gets better service and report our simulation experiment results that shows that our protocol produces performance comparable to 802.11e.
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Chapter 1

Introduction

Real time applications involving voice or video transmissions over a network have stringent requirements in terms of delay, bandwidth and other QoS parameters. Hence, QoS should be provided by the underlying network for proper functioning of those applications. One way to achieve this is to provide QoS at the MAC layer, which makes physical bandwidth usable. Since wireless LANs (WLAN) are very common nowadays, users expect these real time applications to run over WLANs and get the required QoS. But IEEE 802.11, which the is most prevalent WLAN technology, does not have any inherent QoS support.

To tackle the QoS issues, IEEE formed the 802.11e [2] task group which came up with a priority based CSMA/CA scheme to provide differentiated services across different types of applications.

1.1 Motivation

IEEE 802.11e is a much better protocol than IEEE 802.11 in terms of providing QoS. But it is a new standard. Almost all of the current WLAN infrastructure is 802.11 based. Thus, QoS mechanisms based on IEEE 802.11 have to be looked at until 802.11e is available. But such solution should require minimal change to the 802.11 MAC and yet provide good performance for real time applications. We propose one such MAC protocol. Our scheme provides priority to real time flows by using contention window based service differentiation method. In keeping with minimal change philosophy, we do not propose to have differentiation using different IFSs. But it has been found that providing priority through IFS based techniques is more effective than Contention Window (CW) based techniques [3]. This is because such protocols get deterministic differentiation in access times of different priority classes, whereas in CW based schemes, differentiation is probabilistic. Since 802.11e employs both IFS based and CW based priority it is quite effective in providing service differentiation. Hence, we did not expect our scheme to outperform 802.11e, but our protocol is carefully designed to make the performance comparable to 802.11e.

We propose to have two ways of implementing our protocol: single queue per station (SQS) and two queue per station (TQS). In SQS mode, priority is assigned at the station level, i.e., a station will either carry only high priority traffic or only low priority traffic. Implementation of this mode requires very minimal change to existing 802.11 MAC. In TQS mode, a station will have two queues, one for high priority traffic and the other for low priority traffic. Later in the report, we discuss the implementation of this mode in
1.2 Mechanisms to provide QoS in MAC

The IEEE 802.11 [4] MAC uses DCF (Distributed Coordination Function) for media access among the participating network nodes. But DCF alone is neither capable nor suitable for fulfilling the QoS requirements of realtime applications like voice and video. It does not provide any priority and there is no service differentiation between different flows. Generally, the proposed QoS schemes which are based on IEEE 802.11 try to improve DCF functionality. There are primarily three ways in which QoS is provided by modifying DCF based MAC:

- Prioritisation among different classes of traffic: Most of the techniques use different Inter Frame Space (IFSs) or different Contention Window (CWs) or both [1, 5, 6, 7].
- Resource allocation to prioritized classes of data: This is achieved by some distributed variant of Weighted Fair Queuing (WFQ) [8] [9].
- Admission control: Measurement and model based admission control mechanisms are used to provide QoS [10][11][12].

1.2.1 Prioritisation

A class of data traffic can be made higher priority class by assigning a smaller IFS to its data frames, which results in low waiting time. And once the channel becomes idle, it can be seized before any lower priority data frame starts transmission. This is one of the techniques used by 802.11e and by earlier proposed schemes like SCW [7]. Another technique of providing priority is by having different CWs for different classes of data. The scheme proposed by us, falls under this category. There are two ways -

- Contention Window Differentiation (CWD) - The idea is that given two classes of traffic A and B, there are two ranges of CW : $CW_A$ (between $CW_{min,A}$ and $CW_{max,A}$) $CW_B$ (between $CW_{min,B}$ and $CW_{max,B}$). Since Backoff Interval (BI) is a uniformly distributed random number between $CW_{min}$ and $CW_{max}$, the two traffic classes are differentiated by the average BI values. The two CWs could, however, overlap.
- Contention Window Separation (CWS) - In this case the CWs assigned to different priority classes are completely separated.
1.2. Mechanisms to provide QoS in MAC

It has been found that providing priority through IFS based techniques is much more effective and powerful than Contention Window based techniques [3]. The reason is that we have a clear or deterministic separation in access times of different classes whereas in CW based schemes the difference is mostly probabilistic. As 802.11e employs both IFS based and CW based priority it is quite effective in providing QoS and service separation.

The standardized WLAN protocols mostly employ the above mentioned schemes but there are other prioritizing schemes like Black Burst [13] which employ some other interesting mechanisms to provide priorities, but they are generally not compatible with the existing standards.

Pure priority based schemes can lead to the starvation of the lower priority data. In such cases fairness can be guaranteed if the resource or bandwidth share of different priority levels is kept in limit. This can be done by different scheduling mechanisms. One such scheme is DFS (Distributed Fair Scheduling) [8].

1.2.2 Resource allocation

As seen in the previous section, the use of priority alone for providing QoS leads to unfairness for the lower priority data flows or frames. Fairness can be guaranteed if the resource or bandwidth share of different priority levels is kept in limit. This can be done by different scheduling mechanisms.

Simplest form of scheduling is done by allocating specified amount of bandwidth to different classes. It is also known static partitioning (as used in simple implementations of DiffServ etc). Some newer and more complex algorithms are capable of dynamically changing the allotted amount of bandwidth. For example if some class is not fully utilizing the allotted bandwidth, the leftover portion can be given to other classes.

Although Fair Scheduling is well established in centralized systems (for example we have implementations of WFQ), there is still not a well specified or standardized scheme in distributed domain. One such distributed scheme is DFS (Distributed Fair Scheduling) proposed by [8]. In centralized schemes a designated host coordinates access to wireless medium, thus taking care of the fairness among different classes.

1.2.3 Admission control

When Admission Control is in place any new data transmissions or flow are allowed only if the system is able to fulfil its requirements. This scheme protects the ongoing communication from any new flow. Admission control can be both at class level or flow level. This concept is used in Intserv (Integrated Services architecture) to provide QoS in wired scenario.

Admission control schemes require full knowledge for the current state of the network. Generally these schemes are centralized. Some distributed schemes are also proposed, but they have imposed requirement that the stations in network are always able to listen transmissions of every other node, which is difficult to achieve in most of the ad-hoc networks. Infrastructure based wireless LANs can have centralized scheme with access point being used as the central node.
Chapter 2
Related Work in QoS

2.1 IEEE 802.11e

The IEEE 802.11e MAC employs a channel access function, called Hybrid Coordination Function (HCF), which includes a contention based channel access known as EDCA and a contention free channel access mechanism. EDCA has four Access Categories (ACs). Each AC obtains a differentiated channel access due to varying amount of time an AC would sense the channel to be idle and different length of the contention window size during backoff. EDCA supports eight different priorities, which are further mapped into four ACs. Access Categories are achieved by differentiating the arbitration interframe space (AIFS), the initial window size, and the maximum window size. For the AC[i] (i = 0; ...; 3), the initial backoff window size is $CW_{\text{min}}[i]$, the maximum backoff window size is $CW_{\text{max}}[i]$, and the arbitration interframe space is AIFS[i].

Each AC acts as an independent virtual MAC entity and performs the same DCF function, with a different interframe space (AIFS[i]), and a different Contention Window. Each AC has its own backoff counter (BO[i]), which is independent of others. If more than one AC finishes the backoff at the same time, the highest priority AC frame is chosen for transmission by the virtual collision handler. Other lower priority AC frames go to the next round of backoff. Figure 2.1 shows different Access Categories present in 802.11e.

![Different Access Categories in 802.11e (taken from [1])](image)

Figure 2.1: Different Access Categories in 802.11e (taken from [1])
2.2 Black burst (BB)

This scheme is proposed in [13]. The main goal is to minimize the delay of real-time traffic. This scheme imposes some requirements on the high priority STAs, which are:

- All high priority STAs try to access the medium with equal and constant intervals, \( t_{\text{sch}} \).
- The ability to jam the medium for a period of time.

The real time or the high priority nodes use a shorter IFS than the lower priority nodes. After sensing medium to be free the real time nodes do not send their packets directly, rather they sort their access rights by jamming the channel with pulses of energy, known as BB’s. The duration of a BB transmitted by a real-time node is an increasing function of the contention delay experienced by that node, from the instant when an attempt to access the channel has been scheduled until the node starts the transmission of its BB. Thus the node which has waited most gets the opportunity to transmit. In steady state and high load conditions, the stations appear to transmit in a TDM fashion.

2.3 DFS (Distributed Fair Scheduling Scheme)

DFS [8] is based on the IEEE 802.11 MAC and SCFQ:

- The DFS protocol borrows on SCFQ’s idea of transmitting the packet whose finish tag is smallest, as well as SCFQ’s mechanism for updating the virtual time.

- A distributed approach for determining the smallest finish tag is employed, using the backoff interval mechanism from IEEE 802.11 MAC. The essential idea is to choose a backoff interval that is proportional to the finish tag of packet to be transmitted.

2.4 Sliding Contention Window (SCW) for Efficient service differentiation in 802.11

In this technique proposed by [7] the backoff randomness is controlled by providing strict separation between CW ranges of each traffic class i, j, k, etc. Meanwhile, overlapping between CW ranges of the different traffic classes is permitted in order to achieve high medium exploitation in relaxed network conditions. The scheme is shown in figure 2.2. SCW uses a Linear-increase Linear-decrease (LILD) model to adjust the SCW range. Compared to the conventional DCF, each time a flow in TC[i] experiences a high loss rate, SCW[i]'s range is increased by a SF[i] step, until the upper bound reached the maximum window value. When losses are low and packets are transmitted successfully, rather than resetting the contention window, SCW[i]'s range is decreased with the same SF[i] step, until the lower bound reaches \( CW[i]_{\text{min}} \).
2.5. AC scheme

This scheme is proposed by I. Aad and C. Castelluccia [14]. There are three basic subschemes under this:

- **Different backoff increase function:**
  Each priority level has a different backoff increment function. Assigning a short contention window to those higher priority STAs ensures that in most (although not all) cases, high-priority STAs are more likely to access the channel than low-priority ones. Thus improving their service performance.

- **Different DIFS:**
  In this approach, each priority level has a different DIFS. High priority levels are assigned shorter IFS than lower priority levels. The main problem of this scheme is that low priority traffic suffers as long as high priority frames are queued.

- **Different maximum frame lengths:**
  Each STA has a different maximum frame length according to its priority level, therefore, a high priority STA can transmit more information per medium access than a low priority STA. This mechanism is used to increase both transmission reliability and differentiation, however, in a noisy environment, long packets are more likely to be corrupted than short ones, which decreases the service differentiation efficiency.
2.6 DC Scheme

Its a service differentiation scheme proposed by Deng and Chang, which requires minimal modifications of the basic 802.11 DCF. The DC scheme uses two parameters of IEEE 802.11 MAC, the backoff interval and IFS between each data transmission, to provide the differentiation.

Four classes of priorities can be supported by exploiting combinations of two IFSs and two different backoff functions.
Chapter 3

Our Protocol

3.1 Overview

3.1.1 Basic Mechanism

Our protocol is designed to provide two levels of priorities. High priority can be used by real time applications like voice and video, whereas low priority would be used by regular best effort based application like email, FTP etc. Our protocol uses contention window based differentiation mechanism to provide priorities to traffic flows. Basically, it specifies two different contention window (CW) ranges for two priority levels. As shown in Figure 3.1, the high priority class occupies the lower half of the Contention Window range, whereas the low priority occupies the upper half. Higher priority class chooses its backoff from the lower half of the complete Contention Window range. This allows higher priority traffic to have a smaller backoff interval than the lower priority traffic. Thus, the average delay of high priority traffic should be less than that of low priority traffic. Moreover, since the delay is low for higher priority class, it receives relatively higher throughput than the lower priority class. Thus, this MAC protocol basically provides a better quality of service to the higher priority class at the cost of service of the lower priority class.

![Figure 3.1: Different CW Ranges for Different Priorities](image)

3.1.2 Collision Handling

In IEEE 802.11 DCF MAC protocol, when a collision occurs, the contention window range is doubled. The stations involved in collision then choose the backoff value from the larger range, which lowers the probability of collision. In our scheme, however, the CW range is increased in a linear fashion. Thus, after every unsuccessful transmission attempt the current CW range is increased by $CW_{\text{min}}$. Further, while the CW range is increased, the individual CW ranges of priority classes become noncontiguous as shown in Figure 3.2. This Figure shows the effect of collision on the contention window of individual priority...
classes. Before collision, the contention window of high priority flow is from A to B and of low priority is from B to C. After collision, the contention window of both the priority classes become noncontiguous i.e., high priority class gets CW range from A to B and from C to D, whereas low priority class gets CW range from B to C and from D to E. Now we provide the rationale behind two major aspects of our protocol.

3.1.2.1 Linear Increase

In IEEE 802.11 and IEEE 802.11e the increase in CW size after collision is exponential. This decreases the probability of further collision between the same stations. But in our scheme, we increase the CW size linearly. It has been reported that the probability of stations going through four or more successive collision is negligible [15]. Even the probability of having three successive collision is quite low. Moreover, the first two rounds of backoff in exponential and linear increase scheme will have the exact same contention window size. Hence, the performance difference between the two schemes may not be that significant. Linear increase in contention window size helps reducing the delay difference between packets sent from different rounds of backoff, while reducing the probability of collision in subsequent round.

3.1.2.2 Noncontiguous Contention Windows

In our protocol, contention windows of the two priority classes become noncontiguous after collision. This has the following advantages:

- Under high load condition, if a high priority and a low priority frame have collided, then they will not collide again.

- The difference between expected values of backoff for high priority and low priority remains same irrespective of the round of retransmission. This has the nice property that the relative delay performance of the two classes will still remain the same in subsequent backoff rounds. This fact is illustrated in Figure 3.2 by $exp_H$ and $exp_L$. 

Figure 3.2: Effect of Collision on the Contention Window Ranges for Different Priority Classes
3.1.3 Effect of Backoff Countdown on Low priority class

In the proposed scheme, the frames belonging to low priority class always choose a higher backoff value than the high priority frames. This may seem unfair for the low priority flows. Although the low priority frames have to wait longer than the high priority ones, they eventually get a chance to transmit. Figure 3.3 shows the process of countdown of backoff counter of low priority traffic. The low priority frames initially choose a backoff value from CW/2 to CW-1, but after countdown of CW/2 backoff slots, the backoff counter takes a value between 0 to (CW/2) – 1, which is the contention window range for high priority class. Thus, the lower priority frame effectively becomes equivalent to a high priority frame when its backoff counter counts down to a value which is in the range of high priority traffic. This dynamic change in priority helps maintain fairness to the low priority traffic.

![Figure 3.3: Due to Countdown, a Low Priority Eventually Becomes Equivalent to a Frame of High Priority](image)

3.1.4 Management of Contention Window

As mentioned earlier, we provide service differentiation based on contention window assigned to two priority classes. Apart from this, our protocol is very similar to IEEE 802.11 DCF MAC protocol. Let \( CW_i \) denote the total contention window size in a backoff round \( i \). When \( i = 0 \), \( CW_i = CW_0 \) is the minimum total contention window size. For this study, we have taken it as 32, which is the default for IEEE 802.11 DCF. Since we increase total contention window linearly, \( CW_i \) is given by

\[
    CW_i = (i + 1) \cdot CW_0
\]

Note that this \( CW_i \) is the size of the total CW range. This is divided into individual ranges of the two priority classes. Now consider the \( i^{th} \) backoff round. The total CW range is \( CW_i \) and the non-contiguous contention window for the high priority class, denoted by \( CW_i^H \) is given by

\[
    CW_i^H = \begin{cases} 
        0 & \text{to } \frac{1}{2} CW_0 - 1 \\
        CW_0 & \text{to } \frac{3}{2} CW_0 - 1 \\
        2CW_0 & \text{to } \frac{5}{2} CW_0 - 1 \\
        \vdots & \\
        iCW_0 & \text{to } \frac{2i + 1}{2} CW_0 - 1
    \end{cases}
\]

(3.2)
Similarly, the non-contiguous range of contention window for low priority class $CW_i^L$ is given by

$$CW_i^L = \begin{cases} \frac{1}{5}CW_0 & \text{to} \ CW_0 - 1 \\ \frac{2}{5}CW_0 & \text{to} \ 2CW_0 - 1 \\ \frac{3}{5}CW_0 & \text{to} \ 3CW_0 - 1 \\ \vdots \\ \frac{2i + 1}{2}CW_0 & \text{to} \ (i + 1)CW_0 - 1 \end{cases}$$

(3.3)

3.1.5 An Enhancement to Improve Resource Utilization

Keeping the contention window size completely non-overlapping between the high and low priority class may not be good always. For example, at low load condition, the low priority traffic will choose high backoff value due to the non-overlap backoff window. This leads to higher delay and lower throughput. At low load condition, allowing the low priority class to encroach into the CW of high priority class would improve its performance and may not hamper the performance of high priority class significantly. This is the main idea behind the enhancement proposed to our base protocol. Since high priority flow is delay sensitive, we do not allow the same encroachment of high priority CW into low priority CW. Thus, the total CW range remains fixed, but the individual CW range of low priority can step into or come back to its original boundary based on the network load. This dynamic nature of CW of low priority class is shown in Figure 3.4. The increase in

![Figure 3.4: Variation in the size of Contention Window Range of Low priority with Change in Network load](image)

Figure 3.4: Variation in the size of Contention Window Range of Low priority with Change in Network load

the traffic load in the network causes increase in the number of collisions. In other words, the number of collisions per unit time is an indicator of the load on the network. The dynamic size of the Contention Window range of low priority class depends on the number of collision experienced, normalized by number of transmission attempts in an observation period. The minimum size possible is $CW/2$ and maximum is $CW$. Thus, we can have a case where, due to negligible number of collisions, the Contention Window range of low priority class stretches fully from 0 to $CW - 1$. In high load condition, however, the two CW ranges should not overlap. Let overlap factor be denoted by $\Delta$. This $\Delta$ can be defined as the amount of CW which the low priority class encroaches into the region of higher priority. Thus we have,

$$0 \leq \Delta \leq \frac{CW_0}{2}$$

(3.4)
3.1. Overview

The non-contiguous range for low priority class $CW_i^L$ with this enhancement is given by

\[
CW_i^L = \left\{ \begin{array}{ll}
\frac{1}{2} CW_i - \Delta & \text{to } \frac{CW_i - 1}{i} \\
\frac{3}{2} CW_i - \Delta & \text{to } \frac{2 \times CW_i - 1}{i} \\
\frac{5}{2} CW_i - \Delta & \text{to } \frac{3 \times CW_i - 1}{i} \\
\vdots & \\
\frac{2i - 1}{2} CW_i - \Delta & \text{to } \frac{i \times CW_i - 1}{i}
\end{array} \right. \quad (3.5)
\]

This improvement results in an increase in the throughput of BestEffort traffic as shown under subsection 4.0.3 in Figure 4.3.

3.1.5.1 Calculation of Overlapping Factor

The overlapping factor $\Delta$ depends on the number of collisions in the network. Let $k$ be the number of transmission attempts, $c$ be the number of collisions in last $k$ attempts and $t$ be the collision threshold. The amount of overlapping depends inversely on the value of $f$, which is defined as $c/k$ and is known as “collision fraction”. When $f = 0$, there is complete overlap, i.e. $\Delta = CW_0/2$. As $f$ increases, $\Delta$ decreases (discretely in steps) and finally $\Delta$ becomes 0 when $f \geq t$. Figure 3.5 pictorially shows the calculation of overlapping factor $\Delta$. Note that $\Delta$ takes discrete values. That is because of the discrete nature of Contention Window. So if $CW_0 = 32$, $\Delta$ can take values from (0, 1, 2, 3, ..., 16) in order. In Figure 3.5, a very simple case is shown. Here $CW_0 = 8$, so $\Delta$ varies between 0 and 4. When $f = 0$, we have, $\Delta = 4$ and when $f$ becomes 1, $\Delta$ becomes 0.

![Figure 3.5: Calculation of Overlapping Factor](image)
3.2 Performance Evaluation

3.2.1 Single Queue per Station (SQS) Mode

In this mode, there is a single queue per station. In other words, priority is assigned at the station level. Hence, a low (high) priority station will only carry low (high) priority traffic. This scenario is best suited when we have specialized devices in the network. For example a VOIP phone may operate as a high priority station, whereas a network printer will run as a low priority station. To implement this mode in 802.11 MAC is quite simple. All that needs to be done is to change the backoff mechanism of the station, so that the station chooses its backoff value from the appropriate non-contiguous CW. Our implementation in Opnet Simulator [16] took only about ten lines of code change to 802.11 MAC to realize SQS version of our protocol.

3.2.2 Two Queues per Station (TQS) Mode

In this mode, a station has two queues, one for high priority class and the other for low priority class. So, a station has to resolve the contention between two packets belonging to the two priority classes and decide which packet should go out first. This process is termed as virtual collision. The winner packet would then compete with winner packets of other stations in the WLAN.

3.2.2.1 Virtual Collision Mechanism

The Virtual Collision Mechanism (VCM) resolves collision between the packets at the head of the two queues. Figure 3.6 explains the virtual collision process. When a frame comes to the head of the queue, its backoff value is calculated according to the non-contiguous backoff mechanism described earlier. Then the total backoff duration is calculated by adding $DIFS$ time to the backoff value. If the two frame at the head of the two queues have the same total backoff duration, then a virtual collision would occur. In this case, it would recalculate the backoff value. But, unlike 802.11e, the contention window size does not change, while calculating the backoff value after virtual collision. The backoff value of the two packet are chosen from the non-overlapping range of the current CW. When backoff values are recalculated, choosing backoff values from the same current CW still guarantees that there will not be a virtual collision again, due to the non-overlapping nature of the CWs of high and low priority classes. Whereas in 802.11e CW size has to be doubled so that the probability of virtual collision is less in the next round, since the CWs of different Access Categories overlap. Note that virtual collision is resolved by merely recalculating the backoffs, rather than waiting for the backoff counter to count down to zero and at the end, finding out that there is a virtual collision. This saves the time which would have been wasted if the backoff countdown was to happen. If there is no virtual collision, then a winner packet goes through backoff countdown process. This process is very similar to DCF of 802.11. Every time, the medium is idle for a slot time, the backoff counter is decremented by one. When the medium becomes busy, the count down process is stopped. The count down starts again when the medium is sensed idle.
for DIFS amount of time. In Figure 3.6, to keep the flowchart simple, we have not shown the case where there is no need of going into backoff when the medium is free for DIFS amount of time.

![Flowchart Showing the Mechanism of Virtual Collision](image)

Figure 3.6: Flowchart Showing the Mechanism of Virtual Collision

3.2.2.2 Implementation

Implementation of this mode is more complex than the SQS mode because of the presence of two queues. We introduce a thin sub-layer in the MAC layer called Virtual Collision Sub-layer (VCS) which handles virtual collisions described before. The MAC layer needs to inform VCS about events like the medium idle for DFS time, external collision, medium idle for one slot time etc. The VCS sub-layer performs backoff management and hands over frames to MAC which just sends the frame to PHY layer immediately. The current 802.11 MAC will require minimal change and the complex functionality will be handled by VCS sub-layer. Figure 3.7 shows the architecture of our implementation in OPNET simulator. The main functions of the MAC layer in TQS mode of our protocol are:

- Accept a frame from the VCS sub-layer and send it to PHY layer right away. There will not be any backoff performed by this MAC layer. Backoff management will be performed by VCS sub-layer.

- Events like medium busy, medium idle for one slot time, medium idle for DFS time, external collision are communicated to VCS sub-layer. These events are required by VCS sub-layer to do proper backoff management.
3.3 Analytical Model of our Protocol

In this section, we present analytical model of our protocol. Using this model we show that higher priority flow gets better service than low priority flows. Most of the terminology used and the flow of presentation is similar to [17]. The model is Contention Window Based Differentiation Mechanism for providing QoS in Wireless LANs analyzed under saturation throughput and ideal channel conditions. Let $b^H(t)$ and $b^L(t)$ be the stochastic processes representing the backoff time counters for the higher priority and lower priority class in a given station and $s^H(t)$, $s^L(t)$ be the stochastic processes representing the backoff stage (0,...,m) of the respective classes. In our model, we assume, regardless of the number of retransmissions, each packet collides with constant and independent probability $p$. $p$ is the conditional collision probability of collision seen by a packet being transmitted. Note that this conditional probability $p$ will be same for both the priority classes since there is no discrimination among the classes for collision once their transmission starts.

We can model the two dimensional process corresponding to the higher priority class as $\{s^H(t), b^H(t)\}$ with the discrete-time Markov chain of higher priority depicted in Figure 3.8. In this Markov chain, the only non null one-step transition probabilities for high
Figure 3.9: Markov Chain for Low Priority Class

Priority class are

\[
\begin{align*}
P\{i, k| i, k + 1\} &= 1 \quad k \in (0, W_i - 2), i \in (0, m) \\
P\{0, k| i, 0\} &= 2(1 - p)/W_0 \quad k \in (0, \frac{W_0}{2} - 1), i \in (0, m) \\
P\{0, k| i, 0\} &= 0 \quad k \in (\frac{W_0}{2}, W_0 - 1), i \in (0, m) \\
P\{i, k| i - 1, 0\} &= 2p/W_i \quad k = (j + \frac{1}{2}) \cdot \frac{W_i}{i+1}, i \in (1, m), j \in (0, i) \\
P\{i, k| i - 1, 0\} &= 0 \quad k = (j + \frac{1}{2}) \cdot \frac{W_i}{i+1}, (j + 1) \cdot \frac{W_i}{i+1}, i \in (1, m), j \in (0, i) \\
P\{m, k| m, 0\} &= 2p/W_m \\
P\{m, k| m, 0\} &= 0 \\
\end{align*}
\]

Similarly the non null one step transition probabilities for the lower priority class are-

\[
\begin{align*}
P\{i, k| i, k + 1\} &= 1 \quad k \in (0, W_i - 2), i \in (0, m) \\
P\{0, k| i, 0\} &= 0 \quad k \in (0, \frac{W_0}{2} - 1), i \in (0, m) \\
P\{0, k| i, 0\} &= 2(1 - p)/W_0 \quad k \in (\frac{W_0}{2}, W_0 - 1), i \in (0, m) \\
P\{i, k| i - 1, 0\} &= 0 \quad k \in (j + \frac{1}{2}) \cdot \frac{W_i}{i+1}, (j + 1) \cdot \frac{W_i}{i+1}, i \in (1, m), j \in (0, i) \\
P\{i, k| i - 1, 0\} &= 2p/W_i \quad k = (j + \frac{1}{2}) \cdot \frac{W_i}{i+1}, (j + 1) \cdot \frac{W_i}{i+1}, i \in (1, m), j \in (0, i) \\
P\{m, k| m, 0\} &= 0 \quad k = (j + \frac{1}{2}) \cdot \frac{W_m}{m+1}, (j + 1) \cdot \frac{W_m}{m+1}, i \in (1, m), j \in (0, i) \\
P\{m, k| m, 0\} &= 2p/W_m \quad k = (j + \frac{1}{2}) \cdot \frac{W_m}{m+1}, (j + 1) \cdot \frac{W_m}{m+1}, i \in (1, m), j \in (0, i) \\
\end{align*}
\]

The above mentioned transition probabilities represent the noncontiguous nature of the
backoff mechanism of our protocol. The first transition probability in (3.7) accounts for the fact that at the beginning of each slot time, the backoff time is decremented by one. The second probability signifies that a new packet following a successful packet transmission starts with backoff stage 0, and thus the backoff is uniformly distributed between \( 0, \frac{W_0}{2} - 1 \). Note that the range \( \left( \frac{W_0}{2}, W_0 - 1 \right) \) is excluded from the backoff window. The third, fifth and the last probabilities in (3.7) captures the non-contiguity of backoff mechanism. Fourth and sixth transition probability in (3.7) model the system after an unsuccessful transmission. In the fourth transition probability, when an unsuccessful transmission occurs at backoff stage \( i - 1 \), the backoff goes to the next stage and the new initial backoff value is uniformly chosen in the noncontiguous range \((j*\frac{i}{i+1}, (j+1)*\frac{i}{i+1})\) where \( j \in (0, i) \). Finally, the sixth probability shows that once the backoff stage reaches the value \( m \), it is not increased in subsequent packet transmissions.

Let \( b^H_{i,k} = \lim_{t \to \infty} P \{ s^H(t) = i, b^H(t) = k \}, i \in (0, m), k \in (0, W_i-1) \) be the stationary distribution of the chain. It is easy to obtain a closed form solution for the Markov chains. First, the high priority note that:

\[
\begin{align*}
\binom{b^H_{i-1,0}}{b^H_{m-1,0}} & = \binom{b^H_{i,0} \to b^H_{i,0}}{(1-p)b^H_{i,0} \to b^H_{m,0}} = p^{b^H_{i,0}} 0 < i < m \\
\end{align*}
\]

The two states, \( b^H_{i-1,0} \) and \( b^H_{m-1,0} \), can have only two transitions depending on whether the station has a successful transmission or a collision. If the station succeeds at the backoff stage \( (i-1) \), it goes to the first stage of backoff and lands in one of the backoff slots with probability of \( \frac{(1-p)}{W_i/2} \). On the other hand, if there was a collision, it goes to the next stage of backoff (stage \( i \)) and lands in a backoff slot with probability \( \frac{p}{W_{i-1}/2} \). For each \( k \in (1, W_i-1) \), it is

\[
\begin{align*}
b^{H}_{i,k} & = \begin{cases} \\
\frac{W_0}{2} - k & \left( \frac{W_0}{2} \right) \sum_{j=0}^{m} b^H_{j,0} \left( \frac{W_0}{2} \right) - k \right) \sum_{j=0}^{m} b^H_{j,0} \left( \frac{W_0}{2} \right) & 0 \leq k < \frac{W_0}{2} \\
0 & \frac{W_0}{2} \leq k < W_0 \\
0 & \frac{3W_1}{4} \leq k < \frac{3W_1}{4} \\
0 & \frac{3W_0}{4} \leq k < W_1 \\
\end{cases}
\end{align*}
\]
Now as \( W_1 = 2W_0 \) we can rewrite the above equations for simplicity as:

\[
\begin{align*}
\beta_{1,k}^H &= \begin{cases} 
\left( \frac{W_0}{2} - \frac{k}{W_0} \right)^p + \left( \frac{W_0}{2} - \frac{k}{W_0} \right)^p = \left( 1 - \frac{k}{W_0} \right)^p & 0 \leq k < \frac{W_0}{2} \\
\left( \frac{W_0}{2} - \frac{k}{W_0} \right)^p = \frac{p}{2} & \frac{W_0}{2} \leq k < W_0 \\
\left( \frac{3W_0 - k}{W_0} \right)^p = \left( \frac{3}{2} - \frac{k}{W_0} \right)^p & W_0 \leq k < \frac{3W_0}{2} \\
0 & \frac{3W_0}{2} \leq k < 2W_0
\end{cases}
\end{align*}
\]

(3.11)

\[
\begin{align*}
\beta_{2,k}^H &= \begin{cases} 
\left( \frac{W_0}{2} - \frac{k}{3W_0} \right)^p + 2 \left( \frac{W_0}{3} \right)^p = \left( 1 - \frac{k}{3W_0} \right)^p & 0 \leq k < \frac{W_0}{2} \\
2 \left( \frac{W_0}{3} \right)^p = \frac{2}{3}p & \frac{W_0}{2} \leq k < W_0 \\
\left( \frac{3W_0 - k}{3W_0} \right)^p + 1 \left( \frac{W_0}{3} \right)^p = \left( \frac{4}{3} - \frac{k}{3W_0} \right)^p & W_0 \leq k < \frac{3W_0}{2} \\
\frac{W_0}{3}^p = \frac{p}{3} & \frac{3W_0}{2} \leq k < 2W_0 \\
\left( \frac{5W_0 - k}{3W_0} \right)^p + \left( \frac{W_0}{3} \right)^p = \left( \frac{5}{2} - \frac{k}{3W_0} \right)^p & 2W_0 \leq k < \frac{5W_0}{2} \\
0 & \frac{5W_0}{2} \leq k < 3W_0
\end{cases}
\end{align*}
\]

(3.12)

\[
\begin{align*}
\beta_{3,k}^H &= \begin{cases} 
\left( \frac{1 - \frac{k}{2}}{W_0} \right)^p & 0 \leq k < \frac{W_0}{2} \\
\frac{3}{4}p & \frac{W_0}{2} \leq k < W_0 \\
\left( \frac{5}{4} - \frac{k}{1} \right)^p & W_0 \leq k < \frac{3W_0}{2} \\
\frac{1}{2}p & \frac{3W_0}{2} \leq k < 2W_0 \\
\left( \frac{6}{4} - \frac{k}{2} \right)^p & 2W_0 \leq k < \frac{5W_0}{2} \\
\frac{1}{4}p & \frac{5W_0}{2} \leq k < 3W_0 \\
\left( \frac{7}{4} - \frac{k}{1} \right)^p & 3W_0 \leq k < \frac{7W_0}{2} \\
0 & \frac{7W_0}{2} \leq k < 4W_0
\end{cases}
\end{align*}
\]

(3.13)
and so on for $b_{4,k}^H$, $b_{5,k}^H$ etc. We can thus write the generalized equations as

$$b_{i,k}^H = \begin{cases} \frac{W_i - k}{W_i} \cdot 2(1 - p) \sum_{j=0}^{m} b_{j,0}^H & \text{where } k \in (0, \frac{W_i}{2} - 1) \\ 0 & \text{where } k \in (\frac{W_i}{2}, W_i - 1) \end{cases}$$  

(3.14)

where $i = 0$.

$$b_{i,k}^H = \begin{cases} \frac{(j + \frac{1}{2}) W_i}{i + 1} - k + (i - j) \cdot \frac{p \cdot b_{i-1,0}^H}{i + 1} & \text{where } k \in (j \cdot \frac{W_i}{i + 1}, (j + \frac{1}{2}) \cdot \frac{W_i}{i + 1} - 1) \\ (\frac{i - j}{i + 1}) \cdot p \cdot b_{i-1,0}^H & \text{where } k \in ((j + \frac{1}{2}) \cdot \frac{W_i}{i + 1}, ((j + 1) \cdot \frac{W_i}{i + 1} - 1) \end{cases}$$  

(3.15)

where $j \in (0, i), 0 < i < m$ Thus, by relations (3.14), (3.15) and (3.16), all the values $b_{i,k}^H$ are expressed as functions of the value and of the conditional collision probability $p$. $b_{0,0}^H$ is finally determined by imposing the normalization condition as follows.

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k}^H$$  

(3.17)

$$\sum_{k=0}^{W_i-1} b_{0,k}^H = b_{0,0}^H \left( \frac{W_0}{2} - 1 + \sum_{k=0}^{W_0-1} \frac{k}{W_0} \right) = b_{0,0}^H \left( \frac{W_0}{4} + \frac{1}{2} \right)$$  

(3.18)
3.3. Analytical Model of our Protocol

\[ \sum_{k=0}^{W_1-1} b_{1,k}^H = b_{1,0} \left( \frac{W_0}{2} \sum_{k=0}^{W_0-1} \left( 1 - \frac{k}{W_0} \right) + \frac{3W_0}{2} - \frac{k}{W_0} + \sum_{k=0}^{W_0-1} \frac{3W_0}{2} \right) \]

\[ = b_{1,0} \left( \frac{3W_0}{8} + \frac{1}{4} \right) + \left( \frac{W_0}{4} \right) + \left( \frac{W_0}{8} + \frac{1}{4} + 0 \right) \]

\[ = b_{1,0} \left( \frac{3W_0}{4} + \frac{1}{2} \right) \quad (3.19) \]

\[ \sum_{k=0}^{W_2-1} b_{2,k}^H = b_{2,0} \left( \frac{W_0}{2} \sum_{k=0}^{W_0-1} \left( 1 - \frac{2k}{3W_0} \right) + \frac{3W_0}{2} - \frac{2k}{3W_0} + \sum_{k=0}^{3W_0-1} \frac{2W_0-1}{2} \right) \]

\[ + \sum_{k=0}^{2W_0-1} \left( \frac{5W_0}{3} - \frac{2k}{3W_0} \right) + \sum_{k=0}^{3W_0-1} \left( \frac{1}{3} \right) \]

\[ = b_{2,0} \left( \frac{5W_0}{4} + \frac{1}{2} \right) \quad (3.20) \]

Similarly

\[ \sum_{k=0}^{W_3-1} b_{3,k}^H = b_{3,0} \left( \frac{7W_0}{4} + \frac{1}{2} \right) \quad (3.21) \]
\[ \sum_{k=0}^{W_4-1} b_{4,k}^H = b_{4,0} \left( \frac{9W_0}{4} + \frac{1}{2} \right) \]
\[ \sum_{k=0}^{W_5-1} b_{5,k}^H = b_{5,0} \left( \frac{2i+1}{4} + \frac{1}{2} \right) \]
\[ \sum_{k=0}^{W_6-1} b_{6,k}^H = b_{6,0} \left( \frac{m+1}{4} + \frac{1}{2} \right) \]

and so on...

\[ 1 = \sum_{i=0}^{m} \sum_{k=0}^{W_{i+1}-1} b_{i,k}^H = \sum_{i=0}^{m} b_{i,0} \left( \frac{2i+1}{4} + \frac{1}{2} \right) \quad (3.22) \]
This equation can be reduced to a simpler form.

\[
1 = \sum_{i=0}^{m} b_{i,0}^H \left( \frac{(2i+1)W_0}{4} + \frac{1}{2} \right) \\
= \sum_{i=0}^{m} b_{i,0}^H \left( \frac{(2i+1)W_0}{4} + \sum_{i=0}^{m} b_{i,0}^H \frac{1}{2} \right) \\
= W_0 \left( \sum_{i=0}^{m-1} b_{i,0}^H \frac{(2i+1)}{4} + b_{m,0}^H \frac{(2m+1)}{4} \right) + \sum_{i=0}^{m} b_{i,0}^H \frac{1}{2} \\
= W_0 \left( \frac{b_{0,0}^H}{2} \left( \sum_{i=0}^{m-1} i + \frac{p}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{W_0}{2} \left( \frac{b_{0,0}^H}{2} \left( \sum_{i=0}^{m-1} i + \frac{p}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
= \frac{b_{0,0}^H}{2} \left( \frac{(1-p)^2}{2} \left( \sum_{i=0}^{m-1} \frac{p^m}{1-p}(2i+1) + \frac{1}{1-p} \right) \right) \\
=b_{0,0}^H \left[ W_0(1-p-2p^{m+1}) + 2(1-p) \right] \tag{3.24}
\]

We can now express the probability \( \tau^H \) that a higher priority class transmits in a randomly chosen slot time. Since a transmission occurs when the backoff time counter is equal to 0, regardless of the backoff stage, we have

\[
\tau^H = \sum_{i=0}^{m} b_{i,0}^H = b_{0,0}^H \frac{4(1-p)^2}{W(1+p-2p^{m+1}) + 2(1-p)} \tag{3.25}
\]

Similarly for lower priority we can repeat the whole process as,

\[
b_{0,k}^L = \left\{ \begin{array}{ll}
(1-p) \sum_{j=0}^{m} b_{j,0}^L &= (1-p) \sum_{j=0}^{m} b_{j,0}^L, & 0 \leq k < \frac{W_0}{2} \\
\frac{W_0 - k}{\frac{W_0}{2}} (1-p) \sum_{j=0}^{m} b_{j,0}^L &= \left(2 - \frac{k}{\frac{W_0}{2}}\right) (1-p) \sum_{j=0}^{m} b_{j,0}^L, & \frac{W_0}{2} \leq k < W_0
\end{array} \right. \tag{3.26}
\]
3.3. Analytical Model of our Protocol

\[
\begin{align*}
\beta_{1,k}^L &= \begin{cases} 
  p 
  \left( \frac{W_0 - k}{W_0} \right)^p + \frac{1}{2}p 
  \left( \frac{2W_0 - k}{W_0} \right)^p &= p & 0 \leq k < \frac{W_0}{2} \\
  \frac{W_0}{2} \left( \frac{W_0}{W_0} \right)^p &= (3 - \frac{k}{W_0})^p \frac{W_0}{2} \leq k < W_0 \\
  \frac{1}{2}p \left( \frac{W_0}{2} \right)^p &= (2 - \frac{k}{W_0})^p \frac{3}{2}W_0 \leq k < 2W_0
\end{cases}
\end{align*}
\]

(3.27)

\[
\begin{align*}
\beta_{2,k}^L &= \begin{cases} 
  P 
  \left( \frac{W_0 - k}{W_0} \right)^p + 2 * \left( \frac{W_0}{3} \right)^p &= p & 0 \leq k < \frac{W_0}{2} \\
  \frac{1}{2}p \left( \frac{2W_0 - k}{2} \right)^p &= 2 \frac{3}{3}^p & \frac{W_0}{2} \leq k < \frac{3W_0}{2} \\
  \frac{W_0}{3} \left( \frac{2W_0}{3} \right)^p &= (5 - \frac{k}{3W_0})^p \frac{3}{2}W_0 \leq k < 2W_0 \\
  \frac{1}{2}p \left( \frac{3W_0}{3} \right)^p &= \frac{p}{3} & \frac{3W_0}{2} \leq k < \frac{5W_0}{2}
\end{cases}
\end{align*}
\]

(3.28)

\[
\begin{align*}
\beta_{3,k}^L &= \begin{cases} 
  P 
  \left( \frac{W_0}{4} - \frac{k}{2W_0} \right)^p & 0 \leq k < \frac{W_0}{2} \\
  \frac{3}{4}p \left( \frac{3W_0}{4} - \frac{k}{2W_0} \right)^p & \frac{W_0}{2} \leq k < \frac{3W_0}{2} \\
  \frac{3}{4}p \left( \frac{2W_0}{4} - \frac{k}{2W_0} \right)^p & \frac{3W_0}{2} \leq k < 2W_0 \\
  \frac{1}{2}p \left( \frac{3W_0}{2} - \frac{k}{W_0} \right)^p & 2W_0 \leq k < \frac{5W_0}{2}
\end{cases}
\end{align*}
\]

(3.29)

and so on for \(\beta_{4,k}^L, \beta_{5,k}^L\) etc. Thus, by relations (3.14), (3.15) and (3.16), all the values \(\beta_{i,k}^L\) are expressed as functions of the value and of the conditional collision probability \(p\). \(\beta_{0,0}^L\) is finally determined by imposing the normalization condition as follows.

\[
1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \beta_{i,k}^L
\]

(3.30)
3.3. Analytical Model of our Protocol

\[
\sum_{k=0}^{W_0-1} b_{0,k}^L = b_{0,0}^L \left( \frac{W_0}{2} \sum_0^{W_0-1} \left( 2 - \frac{k}{W_0} \right) \right) \\
= b_{0,0}^L \left( \frac{3W_0}{4} + \frac{1}{2} \right) \quad (3.31)
\]

\[
\sum_{k=0}^{W_1-1} b_{1,k}^L = b_{1,0}^L \left( \frac{W_0}{2} \sum_0^{W_0-1} \left( 3 - \frac{k}{W_0} \right) + \frac{3W_0}{2} \sum_0^{W_0-1} \left( 2 - \frac{k}{W_0} \right) \right) \\
= b_{1,0}^L \left( \frac{5W_0}{4} + \frac{1}{2} \right) \quad (3.32)
\]

\[
\sum_{k=0}^{W_2-1} b_{2,k}^L = b_{2,0}^L \left( \frac{W_0}{2} \sum_0^{W_0-1} \left( 4 - \frac{2k}{3W_0} \right) + \frac{3W_0}{2} \sum_0^{W_0-1} \left( 2 - \frac{2k}{3W_0} \right) \right) \\
+ \frac{5W_0}{2} \sum_0^{W_0-1} \left( 2 - \frac{2k}{3W_0} \right) \right) \\
= b_{2,0}^L \left( \frac{7W_0}{4} + \frac{1}{2} \right) \quad (3.33)
\]

Similarly

\[
\sum_{k=0}^{W_3-1} b_{3,k}^L = b_{3,0}^L \left( \frac{9W_0}{4} + \frac{1}{2} \right) \quad (3.34)
\]

\[
\sum_{k=0}^{W_4-1} b_{4,k}^L = b_{4,0}^L \left( \frac{11W_0}{4} + \frac{1}{2} \right)
\]

\[
\sum_{k=0}^{W_5-1} b_{5,k}^L = b_{5,0}^L \left( \frac{2(i+1) + 1}{4} \right) + \frac{1}{2}
\]

\[
\sum_{k=0}^{W_m-1} b_{m,k}^L = b_{m,0}^L \left( \frac{(2(m+1) + 1)W_0}{4} + \frac{1}{2} \right)
\]

and so on. Now

\[
1 = \sum_{i=0}^{m} \sum_{k=0}^{W_{i+1}-1} b_{i,k}^L = \sum_{i=0}^{m} b_{i,0}^L \left( \frac{(2i+1)W_0}{4} + \frac{1}{2} \right) \quad (3.35)
\]
This equation can be reduced to a simpler form.

\[
1 = \sum_{i=0}^{m} b_i^T \left( \frac{(2i + 3)W_0}{4} + \frac{1}{2} \right)
\]

\[
= \sum_{i=0}^{m} b_i^T \left( \frac{(2i + 3)W_0}{4} + \sum_{i=0}^{m} b_i^T \frac{1}{2} \right)
\]

\[
= W_0 \left( \sum_{i=0}^{m-1} b_i^T \frac{(2i + 3)}{4} + b_{m,0}^T \frac{(2m + 3)}{4} \right) + \sum_{i=0}^{m} b_i^T \frac{1}{2}
\]

\[
= W_0 \left( \frac{b_{0,0}^T}{2} \sum_{i=0}^{m-1} i + 1 + \frac{b_{m,0}^T}{2} \frac{p^m}{1-p} \right) + \frac{1}{1-p}
\]

Thus, we have found the corresponding parameter \( \tau_L \) for the low priority class.

\[
\tau_L = \frac{4(1-p)}{W_0(3 - p - 2p^{m+1}) + 2(1-p)}
\]

It can be seen that

\[
\tau_H > \tau_L
\]

This means that at any given slot, the probability of transmission of a higher priority packet is more than the probability of transmission of a lower priority packet. Moreover, since the probability of collision is same for both the priorities, the probability of successfull transmission of the two priority classes are related as

\[
\tau_H * (1 - p) > \tau_L * (1 - p)
\]

Hence, it is obvious that the high priority class will get better service than the low priority class.
Chapter 4
Performance Evaluation

In this Section, we present performance results of our proposed protocol in different application scenarios. We have used Opnet [16] simulation software for our experiment. Since 802.11 does not provide any priority, it is obvious that our protocol will be better than 802.11. Hence, we have compared our scheme with 802.11e only. While running our experiment for 802.11e, AC[3], AC[2] and AC[1] are used for voice, video and best effort traffic respectively, whereas AC[0] has not been used at all. As our scheme is based on 802.11, we modified the existing implementation of 802.11 in Opnet to build our protocol. Our simulation study was done for both the SQS and TQS mode. For both the modes, performance of voice traffic is measured in low load (1.2 Mbps total offered load) scenario and in high load (3.1 Mbps total offered load) scenario. In low load scenario, only two voice flows (64 kbps each) run in the WLAN and rest is best effort flow. In high load scenario, four voice flows (64kbps each) run in the system and rest of the load is offered by best effort traffic. Performance of video traffic was only measured in one load condition (6Mbps total offered load). One video flow offered about 3Mbps load and the rest of the load is offered by best effort traffic. We could not run more than one video flow, because even with two video flows, the system ran at a very heavy load (9Mbps) resulting in heavy packet loss. Since applications use two way communication, running access point in SQS mode adversely affected delay and throughput of high priority flow in the direction of access point to wireless nodes. Hence, in SQS mode of our experiment, all the wireless nodes ran in SQS mode, but the access point ran in TQS mode.

4.0.1 Simulation in SQS Mode

In SQS mode, we have designated some nodes as high priority nodes and others as low priority nodes. High priority nodes send out high priority traffic (e.g., voice), whereas low priority nodes transmit low priority traffic (e.g., best effort). To load the network with high priority traffic, we selectively assign real time applications like Voice and Video to high priority nodes. The amount of code change to realize SQS mode of our protocol in Opnet was very small (less than 10 lines of code). This implies that our protocol can easily be implemented in real 802.11 hardware with a small amount of change in the MAC firmware. The topology used in our simulation is shown in Figure 4.1. It consists of 8 wireless nodes and 1 access point. The parameters like $CW_{min}$, $CW_{max}$ and IFS are configurable in 802.11e, but for our simulation, we have taken their default values as shown in Table 4.1. Table 4.2 shows the parameter values used in our protocol. The specifications of applications and their associated priorities are given in Table 4.3. We
<table>
<thead>
<tr>
<th>Type</th>
<th>AC</th>
<th>IFS</th>
<th>CW_{\text{min}}</th>
<th>CW_{\text{max}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>AC[3]</td>
<td>2</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Video</td>
<td>AC[2]</td>
<td>2</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Besteffort</td>
<td>AC[1]</td>
<td>3</td>
<td>32</td>
<td>1024</td>
</tr>
<tr>
<td>Background</td>
<td>AC[0]</td>
<td>7</td>
<td>32</td>
<td>1024</td>
</tr>
</tbody>
</table>

Table 4.1: 802.11e parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Priority</th>
<th>IFS</th>
<th>CW_{\text{min}} (noncontiguous)</th>
<th>CW_{\text{max}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>High</td>
<td>2</td>
<td>16</td>
<td>1016</td>
</tr>
<tr>
<td>Video</td>
<td>High</td>
<td>2</td>
<td>16</td>
<td>1016</td>
</tr>
<tr>
<td>other</td>
<td>Low</td>
<td>2</td>
<td>32(higher 16)</td>
<td>1024</td>
</tr>
</tbody>
</table>

Table 4.2: parameters used in our protocol

<table>
<thead>
<tr>
<th>Application</th>
<th>Priority</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice over IP</td>
<td>High</td>
<td>64Kbps, G.711</td>
</tr>
<tr>
<td>Video Stream</td>
<td>High</td>
<td>10fr/sec, 1.38Mbps</td>
</tr>
<tr>
<td>FTP</td>
<td>Low</td>
<td>varying</td>
</tr>
<tr>
<td>Telnet</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Database</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Email</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Web</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Table 4.3: Specification of Applications
ran our experiment in different scenarios as explained below.

4.0.1.1 Scenario A

This scenario involves

- A mix of low priority applications (see Table 4.3) to each of four low priority nodes (both in high load and low load situations).

- Four voice applications assigned to four different high priority nodes in high load situation. In low load situation, only two nodes carry voice traffic (other two remain idle).

The average end-to-end delay experienced by voice applications was measured in high and low load situations (Figure 4.4). Note that this delay is measured at network aggregate level and not on per node basis. In low load condition, our protocol and 802.11e have almost the same delay. This is because, at low load, there is very little collision and most of the time the medium is found to be free, hence stations do not go into backoff. In high load condition, it is clear that 802.11e performs better than our protocol. But the delay is only 8% less than our scheme. This is due to the priority mechanism of 802.11e through IFS differentiation. The average delay in our scheme is about 56msec, which is pretty good for voice applications. Figure 4.5 shows the performance of voice application in both 802.11e and our scheme in terms of throughput. Throughputs of the two protocols are almost equal in both high and low load conditions. Since the offered load is within the capacity of the system and the difference of average delay between the two protocols is not significant, in a given observation interval, there is no perceived difference between the throughputs. Figure 4.6 shows the throughput of best effort (BE) traffic in this scenario. In 802.11e, BE traffic gets affected more due to AIFS differentiation. Hence, our protocol provides better throughput most of the times.
4.0.1.2 Scenario B

This scenario involves

- One Video streaming application assigned to one high priority node.
- A mix of low priority applications to each of four low priority nodes.

The total load on the network is approximately 6 Mbps and average end-to-end delay experienced by Video application was measured (Figure 4.7). The delay in our scheme is nearly 10% higher than that of 802.11e. In this situation AIFS based service differentiation of 802.11e is responsible for its better performance. In terms of throughput of BE traffic, Figure 4.9 shows that they are equal under both the protocols.

4.0.2 Simulation in TQS Mode

In TQS mode, nodes are allowed to carry two different traffic classes. The simulation topology for TQS mode is shown in Figure 4.2. It consists of 4 wireless nodes and 1 access point. The specifications of applications and their associated priorities are same as that of SQS mode, given in Table 4.3. Different scenarios were simulated in this mode:

![Topology used in TQS Mode](image)

**Figure 4.2:** Topology used in TQS Mode

4.0.2.1 Scenario A

Following are the configuration in this scenario:

- All the four nodes have one voice application running as high priority class in high load condition, whereas in low load condition, only two nodes carry voice traffic.
- All the four nodes also run best effort traffic as low priority class in both high and low load condition.
Figure 4.10 compares the average end-to-end delay of voice traffic in our protocol to that of 802.11e. The delay of 802.11e is about 8% lower than our protocol in high load condition, but in low condition the two have equal delay. The same reasoning as given in SQS mode applies here. Figure 4.11 compares throughput of voice traffic for the two protocols. Throughput of our protocol is almost the same as 802.11e in both high and low load conditions. BE traffic throughput follows the same trend as scenario A of SQS mode (Figure 4.12).

4.0.2.2 Scenario B

Following are the configurations in this scenario:

- Only one node runs video application as high priority traffic.
- All the four nodes run best effort traffic as low priority class.

Figure 4.13 compares the average end-to-end delay of video traffic in our protocol to that of 802.11e. Although average delay in our scheme is about 10ms more than that of 802.11e, throughput of our protocol is about 15% higher (Figure 4.14). Figure 4.15 shows the throughput of best effort traffic in this scenario. In this scenario, BE traffic throughput under our protocol is less than that in 802.11e (Figure 4.15). This is because, throughput of BE traffic at the node which sends both video and BE traffic is much lower than the other nodes which are carrying only BE traffic.

4.0.3 Improvement in Resource Utilization by using Overlapping CWs

As discussed in 3.1.5 there is an improvement in the throughput of the BestEffort or Low Priority traffic when the overlapping enhancement is utilized. Although, due to improved performance of Low Priority, High Priority suffers, but that is negligible as the load in the system is low. The graph 4.3 shows the performance improvement. The load on the system during this simulation was kept close to 1 Mbps and the threshold $t = 0.2$.

![Best Effort Throughput Improvement](image)

Figure 4.3: Improvement in Resource Utilization
Figure 4.4: Average Delay of Voice Traffic in SQS mode

Figure 4.5: Average Throughput of Voice Traffic in SQS mode

Figure 4.6: Throughput of BE in Scenario A in SQS mode
Figure 4.7: Average Delay of Video Traffic in SQS mode

Figure 4.8: Average Throughput of Video Traffic in SQS mode

Figure 4.9: Throughput of BE in Scenario B in SQS mode
Figure 4.10: Average Delay of Voice Traffic in TQS mode

Figure 4.11: Average Throughput of Voice Traffic in TQS mode

Figure 4.12: Throughput of BE in Scenario A in TQS mode
Figure 4.13: Average Delay of Video Traffic in TQS mode

Figure 4.14: Average Throughput of Video Traffic in TQS mode

Figure 4.15: Throughput of BE in Scenario B in TQS mode
Bibliography


