Priority Access Schemes based on IEEE 802.11 DCF

Yangyang Liu
Department of Computer Science
University of Victoria
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I. Introduction

In recent years, IEEE 802.11 has gained much attention and popularity at an unprecedented rate due to its low cost, ease of deployment and mobility support. However, as a simple and cost-efficient wireless technology for best effort services, the lack of built-in mechanism for support of real-time services makes it unsuitable for the ever-increasing demands of multimedia services and applications, such as VoIP, IPTV that are throughput and delay sensitive.

In order to provide Quality-of-Service (QoS) support to multimedia applications, the Multiband OFDM Alliance (subsequently the WiMedia Alliance) prioritized channel access (PCA) [1] and IEEE 802.11e enhanced distributed channel access (EDCA) [2] are proposed with attempt to provide service differentiation at the MAC layer. Both of these two schemes are based on IEEE 802.11 distributed coordination
function (DCF) [3] only with some simple but effective changes.

Based on DCF procedure, there have been some possible solutions proposed to support differentiated service at the MAC layer. In our report, we summarize these solutions. Some of these solutions are quite simple and easy to implement. The simulation results show their efficiency in providing differentiated services. In addition, we briefly introduce the IEEE 802.11e EDCA and WiMedia PCA followed by an accurate Markov chain model.

The remainder of this report is organized as follows. Section II gives a brief review of IEEE 802.11 DCF and its problem. Possible priority schemes are summarized in Section III followed by introduction to EDCA and PCA in Section IV. Simulation results are presented in Section V and Section VI gives a conclusion.

II. IEEE 802.11 DCF and Its Problems
A. IEEE 802.11 DCF

DCF is the basic MAC mechanism for IEEE 802.11 WLAN. It is based on carrier sense multiple access with collision avoidance (CAMA/CA). In DCF, a station with a frame to transmit would listen to the channel idle for DCF inter-frame space (DIFS). After DIFS idle period, the station would go into a backoff procedure. The backoff time counter is composed of several time slots uniformly chosen from [0,
CW-1], where CW is the current contention window size. For the first transmission attempt of a frame, the CW equals the initial contention window size \( CW_{\text{min}} \). After each unsuccessful transmission, CW would be doubled until it reaches the maximum contention window size \( CW_{\text{max}} \). CW would be reset to \( CW_{\text{min}} \) after every successful transmission attempt or the retransmission number of a frame reaches the retry limit \( L_{\text{retry}} \). In the backoff procedure, the backoff counter would be decremented by 1 in every idle time slot. If the channel becomes busy again in the backoff procedure, the station would freeze its backoff countdown process and resume if the channel becomes idle for DIFS time. When the backoff counter becomes zero, the station would transmit the frame immediately.

Figure 1 shows the basic operation of DCF.

![DCF Procedure](image)

Though widely used, IEEE 802.11 DCF can only provide best-effort services without any QoS guarantee. In DCF, every station statistically has the same probability to access the channel and transmit no matter what kinds of traffic they are sending. Obviously, this kind of channel
access mechanism is challenged by time-bounded services, such as VoIP, video conferencing that require guaranteed bandwidth, delay and jitter. Without prioritized traffic, a station may have to wait an arbitrarily long time before it gets chance to transmit so that these real-time applications may suffer. The results in [4] theoretically show the lower delay limit exists for IEEE 802.11 DCF and indicates the bounded delay cannot be solved by simply increasing data rate without changing the MAC scheme. In addition, the simulation in [5] clearly shows there is no throughput or delay differentiation between different flows (video, audio and background data), and thus no guaranteed QoS service exists in DCF.

III. QoS Support in the MAC Layer

QoS enhancement can be supported by adding service differentiation into the MAC layer. This can be efficiently achieved by modifying the parameters in DCF operation that define how a station or a queue would access the wireless channel. In Figure 1, we can find some fixed parameters that keep the same values for all kinds of stations or traffic flows. These fixed parameters include DIFS, $CW_{\text{min}}, CW_{\text{max}}, L_{\text{retry}},$ contention window increasing factor, backoff time distribution, etc. Since all these parameters keep the same values, the stations using latency IEEE 802.11 DCF statistically have equal probability to access the wireless channel. Currently, there are already some research works focusing on
DCF-based priority schemes. Such kinds of priority schemes may not provide guaranteed QoS support but prioritized QoS due to the contention-based nature. However, prioritized QoS will be useful for those multimedia applications that can live without rigid QoS. Simulations in Section V will show how the DCF-based priority schemes would bias the higher priority traffic in terms of throughput.

According to different periods in DCF operation, we can classify DCF-based priority schemes into four categories: 1) pre-backoff period: IFS-based priority scheme; 2) backoff period: Backoff-based priority schemes; 3) transmission period: transmission opportunity (TXOP)-based priority schemes; 4) hybrid of IFS-based, backoff-based and TXOP-based priority schemes. DCF-based priority schemes would require the packets from application layer be marked with its priority. Packets of video and audio would have higher priority than ordinary data packets.

A. IFS-based Priority Schemes

In the latency DCF, all the stations with frames to transmit would have to wait a fixed DIFS value before entering the backoff procedure. [6] and [7] proposed the arbitrary IFS time before backoff procedure instead of using fixed DIFS time. With arbitrary IFS time, higher priority traffic would wait smaller IFS time while lower priority traffic would have to wait longer IFS time before backoff procedure. Intuitively, IFS-based priority schemes would bias the higher priority frames by letting them
wait less time and enter the backoff procedure earlier than lower priority traffic. IFS-based priority scheme is pretty simple but efficient. Simulation in Section V shows it can provide pretty good differentiated services to frames with different priorities.

B. Backoff-based priority schemes

As mentioned before, there are several fixed parameters in backoff procedure, including \( CW_{\text{min}} \), \( CW_{\text{max}} \), contention-window increasing factor, retry limit, backoff time distribution, etc. There have been some research works investigating how these parameters would affect and provide differentiated services by using different values of these parameters based on the priority of the traffic.

B.1. Differentiated \( CW_{\text{min}} \)

Instead of using the same \( CW_{\text{min}} \) for all kinds of traffic, [8] proposed an analytical model for a simple priority scheme by differentiating the initial contention window size (\( CW_{\text{min}} \)). The idea in [8] is higher priority stations would start with smaller \( CW_{\text{min}} \) while lower priority stations would be assigned larger \( CW_{\text{min}} \). The numerical results in [8] reflect the efficiency of this scheme in providing service differentiations. The simulation results in Section V also show this scheme is pretty efficient though its idea is very simple.

B.2. Differentiated \( CW_{\text{max}} \)

In latency IEEE 802.11 DCF, \( CW_{\text{max}} \) is set to 1023 for all stations. [9]
discusses a simple scheme that higher priority stations would be given smaller $\text{CW}_{\text{max}}$ and lower priority stations would suffer larger $\text{CW}_{\text{max}}$. Intuitively, this scheme would also affect the select of backoff counter when several retransmissions occur.

B.3. Differentiated Contention Window Increasing Factor

The contention window increasing factor in latency DCF is set to 2, which means the current contention window would be doubled for every unsuccessful transmission for a given packet. Another simple scheme investigated in [10] is based on this increasing factor. For higher priority traffic, this increasing factor would be assigned a smaller value than that of lower priority traffic. This tricky scheme leads to the faster increase of the contention window of smaller priority traffic and thus the numerical results in [10] show its effect in providing differentiated services.

B.4. Differentiated Retry Limit

Real-time applications tend to be delay-sensitive and thus long delayed frames would become useless for them. In most cases, too many reties of transmissions of a packet would result in longer delayed frames which in fact would be of no value for the real-time applications and would be only dropped. Due to the delay-sensitive feature of higher priority frames, [10] also proposes a priority scheme in which higher priority stations would be given a smaller value of retry limit whereas lower priority stations may experience more reties. Numerical results in
B.5. Differentiated Backoff Time Distribution

[7] proposes an interesting prioritized backoff time distribution mechanism (PBTDM). Instead of choosing the backoff time uniformly between [0, CW] in latency DCF, the random backoff time in PBTDM is chosen from the current window size using different distributions for different priorities. For formal packets, the distribution of backoff time is uniform whereas the distribution of backoff time for prioritized traffic favours selecting a smaller backoff time. Simulation results in [7] reflect this mechanism is very effective in terms of service differentiations.

B.6. Differentiated Contention Window

Station priorities are supported in [11] by differentiating the contention window which would further affect the choice of backoff time. The proposed idea is the higher priority station use the contention window [0, 2^j-1] and the lower priority station uses window [2^j, 2^j+1-1], where j is the backoff stage. Simulation results in [11] demonstrate the DCF is able to carry prioritized traffic with the proposed scheme.

B.7. Hybrid Schemes Combining the Above Schemes

Obviously some of the schemes mentioned above are independent of each other and thus can be easily incorporated to provide more efficient service differentiations. [10] combines the above schemes B.1, B.3 and B.4 into a more efficient scheme. [9] makes a combination of B.1 and B.4
and the analysis results demonstrate its high efficiency.

C. TXOP-based priority schemes

Transmission opportunity (TXOP) means the time duration in which the channel can be occupied by a station to transmit several frames without the need to contend for the channel after transmission of one frame. IEEE 802.11e EDCA and WiMedia MAC PCA both consider the TXOP in providing prioritized services. Higher priority stations would be assigned much larger TXOP value which allows them to send more frames than lower priority stations as long as they win the chance to transmit.

D. Hybrid priority schemes

In fact the above three categories of priority schemes are parallel to each other and hence any combination of them can be implemented without too much difficulty. [11] tries the scheme that uses different IFS values and contention window sizes for different priority stations. [7] proposes a combined priority scheme that is based on the different IFS values and differentiated backoff time distributions. IEEE 802.11e EDCA and WiMedia MAC PCA adopt a similar priority service scheme in which the different IFS value, different $CW_{min}$ and TXOP are taken into account.

IV. IEEE 802.11e EDCA and WiMedia PCA

Both IEEE 802.11e EDCA and WiMedia PCA are designed to provide
priority channel access to differentiated traffic. The basic idea of them is based on IEEE 802.11 DCF just with some simple but efficient modifications. To achieve differentiation, instead of using fixed DIFS as in the DCF, an Arbitrary IFS (AIFS) is applied. In addition to IFS-based priority scheme, they also adopt backoff-based scheme in which $C_{W_{\text{min}}}$ can be set differently for different priority traffic and TXOP-based priority scheme in which different TXOP values would be assigned to different priority traffic. EDCA and PCA, as hybrid priority schemes, yield higher priority traffic with smaller AIFS value, smaller $C_{W_{\text{min}}}$ but larger TXOP to bias higher priority traffic.

With EDCA and PCA, traffic from application layer would be labelled with different priorities and mapped into up to four access categories (ACs). Accordingly, traffic of different ACs would be buffered in different queues in a given station as shown in Figure 2. Suppose AC$[i]$ has lower priority than AC$[j]$, we have $AIFS[i] \geq AIFS[j]$, $C_{W_{\text{min}}}[i] \geq C_{W_{\text{min}}}[j]$ and at least one of above inequalities must be a real inequality.

![Fig. 2 Four ACs in a given station](image-url)
Each AC within a station behaves like a virtual station: it contends for channel access and starts backoff procedure independently after AIFS idle period. When two or more ACs get the chance to transmit simultaneously, higher priority AC would be granted the opportunity for transmission, while the lower priority AC or ACs suffer from a so-called virtual collision. In other words, each AC would not only contend for channel access with other stations, but also with other ACs within the same station.

In order to investigate the performance of EDCA, some analysis models have been proposed [10, 12, 13, 14]. Among these models, [13] proposes a three-dimensional discrete time markov chain model which accurately takes every detailed operation of EDCA into account.

In this model, time is considered to be slotted equally rather than the general time slots used in Bianchi’s model [15]. The first and second dimensions in this model correspond to the backoff stage and the value of backoff counter respectively. The third dimension in this model is the key part. It indicates the remaining time with time slot unit during either the frozen, transmission, or collision period. Equally slotted time makes the third dimension feasible and these three periods can thus be easily composed of several time slots respectively. The Markov chain is shown in Figure 3. Since each AC within a station acts like a virtual station to access the channel, this Markov chain is for one AC per station rather
than one station. In Figure 3, the states beginning with -2 and -1 represent
the successful transmission period and the procedure before the AC enters
its first backoff stage respectively. Additionally, the $p_i$ and $p_b$ indicate the
collision probability of $AC_i$ and the channel busy probability. They are
assumed independent of the backoff procedure.

Based on this model, a recursive method is proposed to calculate the
mean access delay. This again benefits from the equally slotted time
which makes the time elapsed from one state to the next state in the chain
is one time slot and thus the time delay in one state could be recursively
represented by the time delay from next state or states. From Figure 3 we
can see once the delay from state $(m + h, 0, 0)$ is known, all the delay in
other states can be calculated in a bottom-to-up and left-to-right manner. In fact, for state \((m + h, 0, 0)\), if one packet cannot be sent out at this state, it will be discarded, so the access delay is one time slot. Accordingly, the delay from other states can all be calculated recursively and then the mean access delay would also be achieved.

V. Simulation Results

In this section, several simulations are conducted to validate the performance of priority schemes proposed above using NS2 [16]. The current NS2 edition does not support priority services and thus we use a verified simulation model of IEEE 802.11e EDCA mode for the NS2 proposed in [17]. Though this mode is designed to simulate IEEE 802.11e EDCA, we can manually set all the priority parameters. This means we can investigate each priority parameter individually by fixing other parameters with this EDCA model.

We would mainly investigate the effect of IFS-based scheme and \(CW_{\text{min}}\)-based scheme in providing differentiated services in terms of average throughput. For simplicity and without loss of generality, we assume there are two active ACs in each station. One is AC1 with higher priority and the other is AC0 with lower priority. In the scenario, both AC0 and AC1 in a given station would send CBR traffic of 230 bytes each with time interval of 20 ms. However, the CBR traffic would be
label with different priorities based on whether it belongs to AC0 or AC1. The data rate is set to 11 Mbps.

Average throughput is an important metric when we consider the differentiated services. In this part, we would see how the IFS-based scheme, $CW_{\text{min}}$-based scheme and the hybrid of them affect the average throughput of different ACs.

A. Effect of the AIFS

In order to verify the effects of the AIFS scheme on the average throughput, we fix the AIFS value of AC1 to be 2 ($AIFS[AC1] = 2$) while adjusting the AIFS value of AC0 with 3, 4 and 5. At the same time, we keep all the other priority parameters the same for both AC1 and AC0. Figure 4 demonstrates the average throughput of AC1 and AC0 against the number of stations with different AIFS values for AC0.

Fig. 4 Differentiated Services with different AIFSs
It can be noted in Figure 4 that the AIFS is quite effective to provide service differentiation in terms of average throughput. With the increase of AIFS value of AC0 to 4 and 5, the average throughput of AC1 and AC0 increases and decreases respectively. The larger gap of AIFS values between AC0 and AC1 is, the larger difference of average throughput between AC0 and AC1 will be.

B. Effect of the CW$_{\text{min}}$

With the attempt to see the effect of the CW$_{\text{min}}$, different CW$_{\text{min}}$ values are employed to AC1 while the CW$_{\text{min}}$ of AC0 is set to 31 for all the cases. Figure 5 shows the average throughput of AC1 and AC0 against the number of stations with different CW$_{\text{min}}$ values for AC1.

From Figure 5, we can see CW$_{\text{min}}$ could also bias the higher priority AC effectively. When the CW$_{\text{min}}$ for AC1 is set to the minimum value 7,
the average throughput of AC1 is the largest, while that of AC0 is the smallest. With the decrease of gap of $C_{W_{\text{min}}}$ between AC1 and AC0, the average throughput is also decreased. What needs to be pointed out is in the Figure 5, when the $C_{W_{\text{min}}}$ values for AC0 and AC1 are the same, the performance of AC1 is still better than AC0. This is because the EDCA mode we use realized the virtual collision and AC1 would be granted the chance to access the channel first when AC1 and AC0 in the same station get chance to transmit simultaneously.

C. Hybrid of the IFS scheme and $C_{W_{\text{min}}}$ scheme

Both IEEE 802.11e EDCA and UWB WiMedia MAC adopt the hybrid scheme to strengthen the differentiated services. They combine the IFS-based scheme and $C_{W_{\text{min}}}$-based scheme to achieve this. In this section we would verify the efficiency of this hybrid scheme through simulations. We fix the AIFS value and $C_{W_{\text{min}}}$ of AC1 to be 2 and 15 respectively. We use two sets of AIFS and $C_{W_{\text{min}}}$ for AC0. One is (AIFS[AC0]=3, $C_{W_{\text{min}}}[AC0]=31$) and the other is (AIFS[AC0]=4, $C_{W_{\text{min}}}[AC0]=63$). Figure 6 shows the simulation results.

We can see the hybrid scheme is quite effective especially when the value of AIFS and $C_{W_{\text{min}}}$ of AC0 are set to 4 and 63 respectively. However, from Figure 6 we can find the lower priority traffic may go into starvation when the number of stations becomes large. This simulation result also suggests that the number of ACs, or in other words, the traffic
load, should be limited in order to provide a relatively satisfactory service level both for high-priority and low-priority ACs in [13].

VI. Conclusions

In this report, we summarize several DCF-based priority schemes with a very accurate Markov model introduced. The simulation results in Section V show that the IFS-based and $CW_{\text{min}}$-based schemes are quite effective in terms of differentiated average throughput. In addition, the result of simulation on the hybrid scheme suggests the number of higher priority ACs should be limited in order to prevent lower priority ACs from starvation.

What needs to be pointed out is PCA adopts almost the same idea with EDCA. However with WiMedia MAC, a given station has to access the channel using PCA and DRP (Distributed Reservation Policy)
interchangeably. When we consider performance of PCA in WiMedia MAC, we should take DRP into account as well. This would be our next work both from the Markov chain model and simulation model aspects.

References