

Performance Analysis of An Enhanced IEEE 802.11 Distributed Coordination Function Supporting Service Differentiation

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Abstract. As one of the fastest growing wireless access technologies, Wireless LANs (WLANs) must evolve to support adequate degrees of service differentiation. Unfortunately, current WLAN standards like IEEE 802.11 Distributed Coordination Function (DCF) lack this ability. Work is in progress to define an enhanced version capable of supporting QoS for multimedia traffic at the MAC layer. In this paper, we aim at gaining insight into two mechanisms to differentiate among traffic categories, i.e., scaling the minimum contention window size and the length of the packet payload according to the priority of each traffic flow. We propose an analysis model to compute the throughput and packet transmission delays. In additions, we derive approximations to get simpler but more meaningful relationships among different parameters. Comparisons with simulation results show that a very good accuracy of performance evaluation can be achieved by using the proposed analysis model.

Keyword: Wireless LAN, IEEE 802.11, Quality of Service Guarantee, Service Differentiation

Introduction

One of the major challenges of the wireless mobile Internet is to provide Quality of Service (QoS) guarantees over IP-based wireless access networks [2]. Wireless access may be considered just another hop in the communication path for the whole Internet. Therefore, it is desirable that the architecture supporting quality assurances follows the same principles in the wireless networks as in the wireline Internet, assuring compatibility between the wireless and wireline parts. A good example for such a wireless technology is the IEEE 802.11 Distributed Coordination Function (DCF) standard [3], compatible with the current best-effort service model of the Internet.

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In order to support different QoS requirements for various types of service, a possibility is to support service differentiation in the IEEE 802.11 MAC layer. Some differentiated services-capable schemes for the enhancement of IEEE 802.11 MAC have been proposed [4][5]. In [4], service differentiation is supported by setting different Minimum Contention Window CW_{\min} for different types of services. The work in [5] proposes three service differentiation schemes for IEEE 802.11 DCF. Moreover, in [6], both the Enhanced Distributed Coordination Function (EDCF) and the Hybrid Coordination Function (HCF), defined in the IEEE 802.11e draft, are evaluated. In the literature, performance evaluation of the basic 802.11 MAC protocol has been done by using simulation [7] or by means of analytical models [8]-[12].

By building on previous papers dealing with the analysis of the IEEE 802.11 MAC, we extend the analysis to the Enhanced IEEE 802.11 MAC with service differentiation support. The new results of the presented analysis provide a compact explanation about the effect of the different parameters on the service differentiation.

I. IEEE 802.11 DCF and Enhanced Versions

In the 802.11 MAC sub-layer, two services have been defined: the Distributed Coordination Function (DCF), which supports delay-insensitive data transmissions, and the optional Point Coordination Function (PCF) to support delay-sensitive transmissions. The DCF works as a listen-before-talk scheme, based on CSMA. Moreover, a Collision Avoidance (CA) mechanism is defined to reduce the probability of collisions. Briefly, when the MAC receives a request to transmit a frame, a check is made of the physical and virtual carrier sense mechanisms. If the medium is not in use for an interval of DIFS, the MAC may begin transmission of the frame. If the medium is in use during the DIFS interval, the MAC will select a backoff time and increment the retry counter. The backoff time is uniformly chosen in the range $(0, W - 1)$, W being the contention window. The MAC decrements the backoff value each time the medium is detected to be idle for an interval of one slot time. The terminal starts transmitting a packet when the backoff value reaches zero. After the transmission of a packet, the sender waits for the ACK frame from the receiver after SIFS (plus the propagation delay). If the sender does not receive the ACK within ACK_Timeout, or if a different packet is on the channel, it reschedules the packet transmission according to the given backoff rules. If there is a collision, the contention window is doubled, a new backoff interval is selected. At the first transmission attempt, W is set equal to a value CW_{\min} called minimum contention window. After each unsuccessful transmission, W is doubled, up to a maximum value $CW_{\max} = 2^m \cdot CW_{\min}$.

The basic DCF method is not appropriate for handling multimedia traffic requiring guarantees about throughput and delay. Because of this weakness, work is in progress to define an enhanced version capable of supporting QoS [13]. In this paper, we are not interested in exploring all details of the new proposed standard but to gain insight into two of the mechanisms, i.e. scaling minimum contention window sizes and lengths of packet payload according to the priority of each traffic category.

II. Performance Analysis

We assume that the channel conditions are ideal (i.e., no hidden terminals and capture) and that the system operates in saturation: a fixed number of stations always have a packet available for transmission.

L ($L \geq 1$) different types of traffic flows are considered with n_i traffic flows for traffic type i ($i=1,2,\dots,L$). Let $b_i(t)$ be the stochastic process representing the backoff time counter for a given traffic flow with type i . Moreover, let us define for convenience $W_i = CW_{\min,i}$ as the minimum contention window for traffic type i . Let m_i , “maximum backoff stage” be the value such that $CW_{\max,i} = 2^{m_i} \cdot W_i$, and let $s_i(t)$ be the stochastic process representing the backoff stage ($0,1,\dots,m_i$) for a given traffic flow with type i .

The key approximation in the model is that, at each transmission attempt for a traffic flow of type i , regardless of the number of retransmissions suffered, each packet collides with constant and independent probability p_i . This assumption has been shown by simulation in [12] to be very accurate as long as W_i and n_i get larger. In this paper, p_i is referred to as conditional collision probability: the probability of a collision seen by a packet belonging to a traffic flow with type i at the time of its being transmitted on the channel.

We use a two-dimensional discrete-time Markov chain to model the behavior of a traffic flow with type i . The states are defined as couples of two integers $\{s_i(t), b_i(t)\}$.

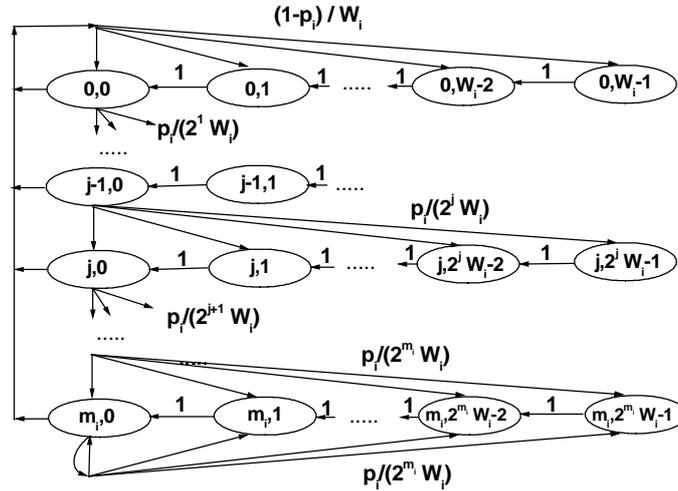


Fig. 1 Markov model of backoff process for traffic type i

The Markov chain can be presented as follows (see Fig.1)

Case 1: Before packet transmissions,

$$P\{j, k | j, k+1\} = 1 \quad k \in [0, 2^j \cdot W_i - 2], j \in [0, m_i] \quad (1.1)$$

Case 2: After packet transmissions,

$$\begin{cases} P\{j+1, k | j, 0\} = \frac{p_i}{2^{j+1}W_i} & (j < m_i), (k \in [0, 2^{j+1} \cdot W_i - 1]) \end{cases} \quad (2.1)$$

$$\begin{cases} P\{m_i, k | m_i, 0\} = \frac{p_i}{2^{m_i}W_i} & (k \in [0, 2^{m_i} \cdot W_i - 1]) \end{cases} \quad (2.2)$$

$$\begin{cases} P\{0, k | j, 0\} = \frac{(1-p_i)}{W_i} & (j \in [0, m_i]), (k \in [0, W_i - 1]) \end{cases} \quad (2.3)$$

Based on the above descriptions of state transitions for traffic flows, we can solve the Markov chain for type i traffic. Let $q_i(j, k)$, $j \in [0, m_i]$ and $k \in [0, 2^j W_i - 1]$, be the stationary distribution of the chain. It can be found that all the state probabilities

can be expressed by $q_i(0, 0)$. Because $\sum_{j=0}^{m_i} \sum_{k=0}^{2^j W_i - 1} q_i(j, k) = 1$, we have:

$$q_i(0, 0) = \frac{2(1-2p_i)(1-p_i)}{(1-2p_i)(W_i+1) + p_i W_i [1 - (2p_i)^{m_i}]} \quad (3)$$

Let τ_i be the probability that a station carrying type i traffic transmits in a randomly chosen slot time. We have:

$$\tau_i = \sum_{j=1}^{m_i} q_i(j, 0) = \frac{2(1-2p_i)}{(1-2p_i)(W_i+1) + p_i W_i [1 - (2p_i)^{m_i}]} \quad (4)$$

With the above probabilities defined, we can express packet collision probabilities p_i as:

$$p_i = 1 - (1 - \tau_i)^{n_i - 1} \prod_{j=1, j \neq i}^L (1 - \tau_j)^{n_j} \quad (5)$$

After combining equations (4) and (5) and by using a numerical method, we can get all the values for p_i and τ_i .

Let P_r be the probability that there is at least one transmission in the considered slot time. We have

$$P_r = 1 - \prod_{j=1}^L (1 - \tau_j)^{n_j} \quad (6)$$

The probability P_s that there is one and only one transmission occurring on the channel can be given as

$$P_s = \frac{\sum_{j=1}^L \left\{ n_j \tau_j (1 - \tau_j)^{n_j - 1} \cdot \prod_{k=1, k \neq j}^L (1 - \tau_k)^{n_k} \right\}}{P_r} \quad (7)$$

Moreover, we define $P_{str,i}$ as the probability that there is one and only one transmission of a traffic flow with type i occurring on the channel, and we have

$$P_{str,i} = n_i \tau_i (1 - \tau_i)^{n_i - 1} \cdot \prod_{k=1, k \neq i}^L (1 - \tau_k)^{n_k} \quad (8)$$

The normalized system throughput S can be expressed as

$$S = \frac{\sum_{i=1}^L P_{str,i} \cdot E[P_{Len,i}]}{(1 - P_{tr})\sigma + \sum_{i=1}^L P_{str,i} \cdot T_{s,i} + (P_{tr} - \sum_{i=1}^L P_{str,i}) \cdot T_c} = \sum_{i=1}^L S_i \quad (9)$$

where S_i denotes the throughputs contributed by type i traffic flows. $E[P_{Len,i}]$ is the average duration to transmit the payload for type i traffic (the payload size is measured with the time required to transmit it). If all packets of type i traffic have the same fixed size, we have $E[P_{Len,i}] = P_{Len,i} \cdot \sigma$ is the duration of an empty slot time. $T_{s,i}$ is the average time of a slot because of a successful transmission of a packet of a traffic flow with type i . $T_{s,i}$ can be expressed as

$$T_{s,i} = PHY_{header} + MAC_{header} + E[P_{Len,i}] + SIF + \delta + ACK + DIF_1 + \delta \quad (10)$$

where δ is the propagation delay. T_c is the average time the channel is sensed busy by each station during a collision, and it can be expressed as

$$T_c = PHY_{header} + MAC_{header} + E[P_{c_Len}] + DIFS + \delta \quad (11)$$

where $E[P_{c_Len}]$ is the average length of the longest packet payload involved in a collision. With the definition of the set $\Omega_1(k)$ as

$$\Omega_1(k) \equiv \{c_1, \dots, c_L \mid \sum_{i=1}^L c_i = k, 0 \leq c_i \leq n_i, i = 1, \dots, L\}$$

$E[P_{c_Len}]$ can be given as:

$$E[P_{c_Len}] = \frac{\sum_{k=2}^{n_1 + \dots + n_L} \sum_{\Omega_1(k)} \left\{ \prod_{i=1}^L \binom{n_i}{c_i} \cdot \tau_i^{c_i} (1 - \tau_i)^{n_i - c_i} \cdot \max[\theta(c_1)P_{Len,1}, \dots, \theta(c_L)P_{Len,L}] \right\}}{P_{tr} - \sum_{i=1}^L P_{str,i}} \quad (12)$$

where

$$\theta(x) \equiv \begin{cases} 1 & x > 0 \\ 0 & x = 0 \end{cases}$$

Next, we analyze the average packet delay. We define delay $T_{D,i}$ as the average time period between the instant of a traffic flow with type i beginning its backoff procedure to transmit a packet to the instant that the packet can be transmitted without collision. Therefore, $T_{D,i}$ dose not include the transmission time for the packet.

It can be easily found that there is a simple relationship between $T_{D,i}$ and the throughput S_i . We have the relation as:

$$s_i \equiv \frac{S_i}{n_i} = \frac{E[P_{Len,i}]}{T_{D,i} + T_{s,i}} \quad (13)$$

Therefore, $T_{D,i}$ can be given as

$$T_{D,i} = \frac{E[P_{Len,i}]}{s_i} - T_{s,i} \quad (14)$$

III. Approximation Analysis

In order to gain a deeper insight into the whole system, we make some approximations to get simpler but more meaningful relationships among different parameters. We start from equation (5) to derive:

$$(1 - p_i)(1 - \tau_i) = (1 - p_j)(1 - \tau_j) = \prod_{j=1}^L (1 - \tau_j)^{n_j} \quad (1 \leq i, j \leq L) \quad (15)$$

From the above equation, it can be seen that if $\tau_i \neq \tau_j$, then we must have $p_i \neq p_j$. When the minimum contention window size $W_i \gg 1$ and $W_j \gg 1$, the transmission probabilities τ_i and τ_j are small, that is, $\tau_i \ll 1$ and $\tau_j \ll 1$. Therefore, from equation (15), we have the following approximation

$$p_i \approx p_j \quad (16)$$

Furthermore, when $W_i \gg 1$, $W_j \gg 1$ and $m_i \approx m_j$, we have the following approximation based on equation (4)

$$\frac{\tau_i}{\tau_j} \approx \frac{W_j}{W_i} \quad (17)$$

From equations (5) and (9), we have

$$\frac{S_i}{S_j} = \frac{P_{str,i} \cdot E[P_{Len,i}]}{P_{str,j} \cdot E[P_{Len,j}]} = \frac{n_i \tau_i (1 - \tau_j) E[P_{Len,i}]}{n_j \tau_j (1 - \tau_i) E[P_{Len,j}]} \approx \frac{n_i \tau_i E[P_{Len,i}]}{n_j \tau_j E[P_{Len,j}]} \approx \frac{n_i W_j E[P_{Len,i}]}{n_j W_i E[P_{Len,j}]} \quad (18)$$

Then, we have

$$\frac{s_i}{s_j} \approx \frac{\frac{E[P_{Len,i}]}{W_i}}{\frac{E[P_{Len,j}]}{W_j}} \quad (19)$$

From the above equation, we can see that the throughput differentiation is mainly determined by the scaling of minimum contention window sizes and the length of packet payloads.

Moreover, from equation (14) and (19), we can see that under the conditions $T_{s,i} \ll \frac{E[P_{Len,i}]}{s_i}$ and $T_{s,j} \ll \frac{E[P_{Len,j}]}{s_j}$, which holds when the number of traffic flows $n_i \gg 1$ and $n_j \gg 1$, we have

$$\frac{T_{D,i}}{T_{D,j}} \approx \frac{\frac{E[P_{Len,i}]}{s_i}}{\frac{E[P_{Len,j}]}{s_j}} \approx \frac{W_i}{W_j} \quad (20)$$

Equation (20) is another important approximation relationship obtained. From above equation, we can see that packet delay differentiation among different types of traffic flows is mainly determined by the ratio of the corresponding minimum contention window sizes.

IV. Results And Discussions

In this section, we present some simulation and numerical results according to our analysis model. In our examples, we assume that two types of traffic coexist in the system. The parameters for the system are summarized in Table 1 based on IEEE 802.11b.

Table 1.
System Parameters

MAC Header	272 bits
PHY Header	192 μ s
ACK	112 bits +PHY header
Channel Bit Rate	11Mbps
Propagation Delay	1 μ s
Slot Time	20 μ s
SIFS	10 μ s
DIFS	30 μ s

In Fig. 2 and Fig. 3, we validate our proposed analysis model by comparing simulation results and numerical results. For our simulator, which is implemented by using C++, we consider that there are 20 stations, 10 of them carrying type 1 traffic and the others carrying type 2 traffic. In the simulation, ideal channel conditions (i.e., no hidden terminals and capture) are assumed. The other parameters are set as follows: $W_2 = 1024$, $E[P_{Len,1}] = 2000 \text{ bytes}$, $E[P_{Len,2}] = 1000 \text{ bytes}$, $m_1 = m_2 = 8$. Different simulation values are obtained by varying the minimum contention window size W_1 . Each simulation value is obtained by running our simulator to simulate the actual behavior of the system within the period of 30 minutes. In Fig. 2, the total system

throughput S and throughput S_1 are shown versus W_1 . In Fig. 3, average packet delays $T_{D,1}$ and $T_{D,2}$ are shown versus W_1 . As expected, when W_1 decreases, traffic flows with type 1 occupy larger portion of channel resources. From these two figures, we can see that the simulation results agree so well with the theoretical ones that they overlap, especially in the case of larger W_1 , which justifies the assumption made in section III.

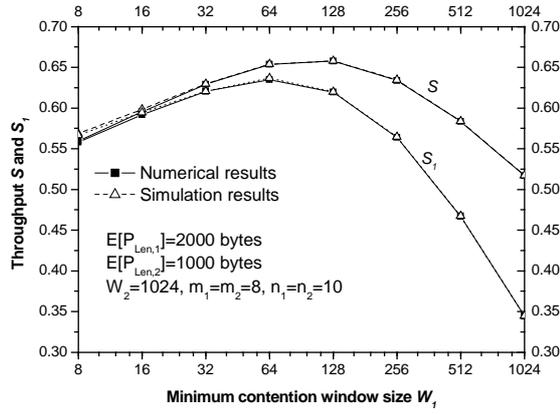


Fig. 2 Throughput S and S_1 versus W_1

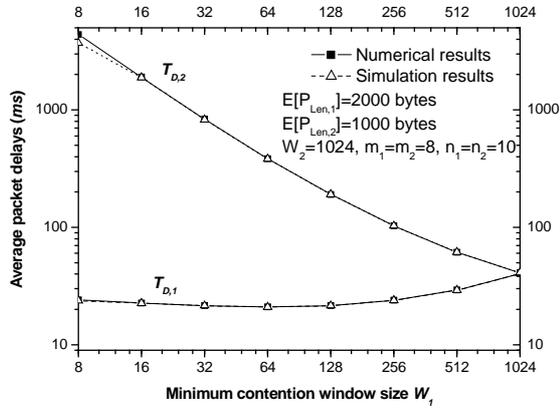


Fig. 3 Average packet delays $T_{D,1}$ and $T_{D,2}$ versus W_1

In Fig. 4 to Fig. 5, we keep the total number of traffic flows constant, and we change the number n_1 of traffic flows with type 1. In Fig. 4, throughputs s_1 and s_2 versus the number of traffic flows n_1 are shown with the variation of W_1 . In Fig. 5, packet delays $T_{D,1}$ and $T_{D,2}$ are shown with the variation of W_1 . We can see that when W_1 decreases, traffic flows with type 1 gain priority over type 2 traffic flows:

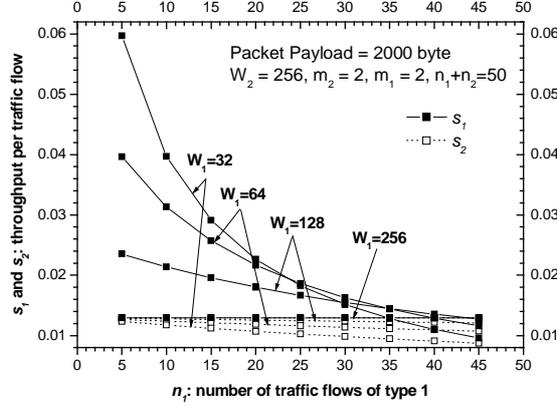


Fig. 4 Throughput s_1 and s_2 versus the number of traffic flows n_1

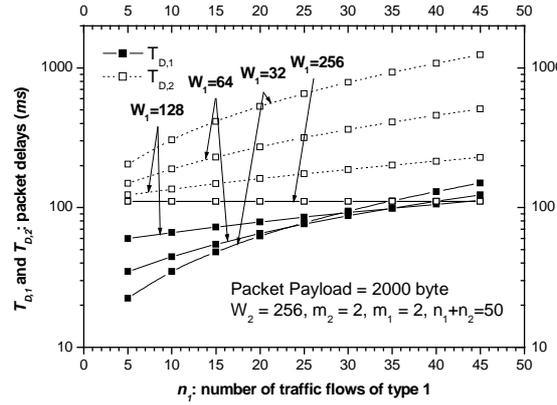


Fig. 5 Packet delays $T_{D,1}$ and $T_{D,2}$ versus the number of traffic flows n_1

throughput s_1 becomes larger than s_2 , and packet delay $T_{D,1}$ becomes smaller than $T_{D,2}$. However, in the case of large n_1 (such as $n_1 > 40$), both the performance on throughput and packet delays are worse than the case of $W_1 = W_2 = 256$, which indicates that providing service differentiation with very large number of traffic flows belonging to the higher priority group makes the system performance worse than in the case of no service differentiation support. The reason is that with the increase of n_1 , collision rates p_1 and p_2 increase drastically, reducing the bandwidth utilization. If the number of traffic flows with higher priority is sufficiently small, both throughput and packet delays for higher priority traffic are improved significantly with only small influence on traffic flows with lower priority. Therefore, the number of traffic flows with higher priority must be strictly controlled to only small proportions of the total number of traffic flows by suitable access control schemes.

V. Conclusions

We propose an analysis model to compute the throughput and packet transmission delays in a WLAN with Enhanced IEEE 802.11 Distributed Coordination Function, which supports service differentiation. In our analytical model, service differentiation is supported by scaling the contention window and the packet length according to the priority of each traffic flow. Comparisons with simulations results show that good accuracy of performance evaluations can be achieved by using the proposed analysis model.

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