

Performance Analysis of IEEE 802.11e Enhanced Distributed Coordination Function

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Abstract—The IEEE 802.11e working group aims to enhance the current 802.11 MAC to support the integrated data and voice (or video) communications. Till now a draft of the IEEE 802.11e EDCF has been proposed. In this paper, we evaluate the performance of the EDCF by dividing the traffic into two categories, namely real-time packets and non real-time packets, and use an analytical model to quantify the performance of both IFS priority and CW priority in the EDCF. We also propose a new priority scheme, which allows the user to continuously send real-time packets. We define the maximum number of real-time packets that a user can continuously send to get a good balance between the fairness and the priority. Our proposed scheme is shown to provide much better results than IEEE 802.11e EDCF.

I. INTRODUCTION

Recently, the concept of wireless networking has become immensely popular and there is an increased interest in the integrated data and voice communications. Multimedia services (e.g., video, voice, audio, and data) are growing rapidly in wireless Local Area Networks (WLANs). IEEE 802.11 as a standard for WLANs, provides a detailed medium access control (MAC) and physical layer (PHY) specification [1]. In the IEEE 802.11 MAC layer protocol, the basic access method is the distributed coordination function (DCF) which is based on the mechanism of carrier sense multiple access with collision avoidance (CSMA/CA). The standard also defines an optional point coordination function (PCF), which is a centralized MAC protocol supporting collision free and time bounded services.

For different types of applications, there are different requirements for the quality of service (QoS). For example, real-time applications such as voice are delay sensitive. However, the delay is not critical for non real-time applications such as ftp and some delays can be tolerated. In WLANs, it is challenging to satisfy individual QoS requirements as wireless links have variable characteristics due to noise and distortion of signal propagation [2]. IEEE 802.11 DCF can only provide best-effort service and cannot guarantee QoS. How to guarantee the QoS requirement has gained more and more attentions. IEEE 802.11e working group is engaged in such work to enhance the MAC performance to support the integrated service [3]. Till now, this group proposed a draft of IEEE 802.11e, in which enhanced distributed coordination function (EDCF) is included. EDCF tries to implement service differentiation by classifying the traffic into different categories with different

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priorities.

In the literature, service differentiation in WLANs has been discussed in [2][4][5][6] and most proposed priority channel access schemes are based on Interframe Space (IFS) and "backoff counter". It was proposed in [2] that different priority packets use different IFSs. High priority packets use IFS while low priority packets use the sum of IFS and the maximum contention window (CW) of high priority packets. This scheme wastes available network capacity to ensure the transmission of high priority packets. Another article [4] mainly focused on backoff. The authors used simulation to run a set of contention windows for high priority traffic and low priority traffic. They have shown that by setting different values of the minimum contention window and the maximum contention window for different traffic classes, different levels service can be achieved. A priority scheme is proposed in [5] by modifying the backoff stage so that different priority packets use different contention window. In this scheme, high priority packets use the contention window $[0, 2^{i+1}-1]$ while low priority packets use the contention window $[2^{i+1}, 2^{i+2}-1]$, where i is the number of consecutive times that the packet attempts to send. The authors primarily used simulation to evaluate the performance. The drawback of this scheme is that even there are no real-time packets in the system, the contention window for non real-time packets is unnecessarily large, which means the waste of bandwidth. Reference [6] implemented priority based on Interframe Space. Real-time packets contend for access to the channel with "black bursts". It did not consider the priority based on backoff.

The proposed IEEE 802.11e EDCF is also based on IFS priority and CW priority. There are some discussions about EDCF in [7][8] and they are mainly based on simulations. In this paper, we divide the traffic into two groups, namely real-time packets (e.g., video) and non real-time packets (e.g., data). We provide an analytical model to quantify the performance of EDCF and at the same time propose a new priority scheme called ultimate EDCF (UEDCF), which allows the user to continuously send real-time packets. In our EDCF scheme, we define the maximum number of real-time packets that a user can continuously send to get a tradeoff between the fairness and the priority. Probability theory is widely used to analyze the throughput and the delay [9][10][11]. Our analytical model is also based on the probability theory. We validate our analytical results by doing extensive simulations.

The paper is organized as follows. In the next section, we briefly describe access mechanisms of the DCF. In Section III,

we present an overview of EDCF. Section IV introduces our analytical models for computing the average delays of different types of packets. In Section V, we present and evaluate our proposed scheme. Numerical results and discussions are given in Section VI. Finally we conclude the paper in Section VII.

II. IEEE 802.11 DISTRIBUTED COORDINATION FUNCTION

The IEEE 802.11 MAC layer is designed to support multiple users contending for access to a shared medium. The DCF in the IEEE 802.11 MAC layer protocol primarily employs a CSMA/CA which works on a "listen before talk" scheme. To transmit a packet, a station must sense the medium to determine if other stations are transmitting and must ensure that the medium is idle for the specified distributed coordination function interframe space (DIFS) duration before transmitting. If a station with a packet to transmit initially senses the channel to be busy; then the station waits until the channel become idle for DIFS period, and then chooses a random "backoff counter" which determines the amount of time the station must wait until it is allowed to transmit its packet. During the period in which the channel is clear, the transmitting station decreases its backoff counter. (When the channel is busy, it does not decrease its backoff counter. It can decrease its backoff counter again only after the channel is clear for DIFS). This process is repeated until the backoff counter reaches zero and the station is allowed to transmit. The idle period after a DIFS period is referred to as CW.

The IEEE 802.11 MAC layer protocol adopts Exponential Backoff. CW starts with CW_{min} , which is defined as the minimum contention window. Then, CW is doubled each time the station experiences a collision until CW reaches CW_{max} which is the maximum contention window. When CW is increased to CW_{max} , it remains the same even if there are more collisions. After every successful transmission, CW is reset to the initial value CW_{min} .

The DCF has two schemes for packet transmission. The basic scheme is a two-way handshaking technique. In this scheme, if a station has a packet to transmit, it waits for a DIFS idle duration of the medium and then transmits its packet. When the packet is received successfully, the destination station sends a positive acknowledgement (ACK) to the sending station after a short interframe space (SIFS). ACK is necessary because, in the wireless medium, the sender cannot determine if a packet has been successfully received by listening to its own transmission.

The second scheme is based on a four-way handshaking that avoids the "hidden terminals" problem [12]. In this scheme, whenever a packet is to be transmitted, the transmitting station first sends out a short request-to-send (RTS) packet containing information on the length of the packet. If the receiving station hears the RTS, it responds with a short clear-to-send (CTS) packet. After this exchange, the transmitting station sends its packet. When the packet is received successfully, the receiving station transmits an ACK

packet. This back-and-forth exchange is necessary to avoid the "hidden terminals" problem.

III. ENHANCED DISTRIBUTED COORDINATION FUNCTION

IEEE 802.11e working group has developed EDCF to enhance the access mechanism of IEEE 802.11 so that the service could be differentiated. The basic idea is to introduce Traffic Categories (TC) and provide different priorities to different TCs. EDCF has two priority schemes, one of which is IFS priority scheme, the other is CW priority scheme. In the IFS priority scheme, an Arbitration Interframe Space (AIFS) is used and a station can send a data packet or start to decrease its backoff counter after it detects the channel being idle for an AIFS. The AIFS is at least DIFS, and can be adjusted for each TC according to the corresponding priority. Thus, the stations with shorter AIFS have a higher priority to access the channel than the stations with longer AIFS. The CW priority scheme implements service differentiation by using different CW_{min} between TCs. Since CW is used to determine the waiting time before a station is allowed to transmit its packet, smaller CW means higher priority. In IEEE 802.11e, a new CW for each TC is derived by

$$\text{newCW}[\text{TC}] \geq \text{oldCW}[\text{TC}] * 2.$$

IEEE 802.11e is similar to IEEE 802.11 in that CW cannot exceed the CW_{max} .

IV. PERFORMANCE ANALYSIS

In this section, we first analyze performance of IEEE 802.11 DCF. Then, we evaluate the performance of IEEE 802.11e EDCF.

A. Performance analysis of IEEE 802.11 protocol

We introduce an analytical model for IEEE 802.11 MAC protocol with an assumption that no hidden-terminals problem is present in the system. Therefore, we use the basic CSMA/CA mechanism. Note that here we don't consider service differentiation. We assume there are N stations in the system contending for one shared channel and each packet has a fixed length. We also assume that each station always has a packet available for transmission and no capture is permitted which means that a station must wait a random backoff time between two consecutive transmissions. We define delay D as the time interval beginning from a packet is ready to transmit till it is received successfully. Because each station always has a packet available for transmission and no capture is permitted, each packet will experience at least one backoff. We assume that each packet collides with constant and independent probability p . It is intuitive that this assumption leads to more accurate results as long as CW_{min} and N get larger [13].

In [14], an analytical model is developed to compute the collision probability p and the throughput S . Let T_p be the length of a packet, T_{slot} be the length of one slot, T_{DIFS} be the length of DIFS, T_{SIFS} be the length of SIFS, and T_{ACK} be the

length of ACK. The probability p and throughput S are given as:

$$p \cdot \frac{1-p-2^m \cdot p^{m+1}}{1-2 \cdot p} = \frac{2}{CW_{\min}} \cdot \left(1 + \frac{2}{3} \cdot N\right) \cdot \frac{N-1}{N} \quad (1)$$

and

$$S = \frac{2 \cdot (1-p)}{2-p} \cdot \frac{T_p}{T_{\text{DIFS}} + T_p + T_{\text{SIFS}} + T_{\text{ACK}} + \frac{CW_{\min}}{N+1} \cdot T_{\text{slot}}}, \quad (2)$$

where m is used to determine the maximum contention window and it satisfies

$$CW_{\max} = 2^m \cdot CW_{\min}.$$

Since

$$S = \frac{N \cdot T_p}{D}, \quad (3)$$

substituting S with (2), we directly get the average delay D

$$D = N \cdot \frac{2-p}{2(1-p)} \cdot (T_{\text{DIFS}} + T_p + T_{\text{SIFS}} + T_{\text{ACK}} + \frac{CW_{\min}}{N+1} \cdot T_{\text{slot}}). \quad (4)$$

As we can see, the collision probability p only depends on m , N and CW_{\min} ; and the average delay D is also related to m , N and CW_{\min} . The maximum contention window size CW_{\max} has the minimal effect on p and S [14]. So CW_{\max} also has the minimal effect on the average delay D . Since the throughput can be easily computed by (3), we will only focus on the delay performance in our following discussions.

B. Delay analysis for IEEE 802.11e EDCF

1) IFS priority scheme

In our analysis, we classify the traffic into two categories, namely real-time traffic and non real-time traffic. To implement service differentiation, we let AIFS for the real-time packets be DIFS and AIFS for the non real-time packets be DIFS+SLOT. We evaluate this priority scheme by computing the average delays for real-time packets and non real-time packets.

Suppose at each station, the fraction of the real-time packets is R , and that of the non real-time packets is $(1-R)$. Since each station always has a packet available to transmit, there will be $N \cdot R$, stations having real-time packets and $N \cdot (1-R)$, stations having non real-time packets to contend for the channel at a time. The AIFS for real-time packets is one slot shorter than the AIFS for non real-time packets. According to CSMA/CA, real-time packets can decrease the backoff counter after an idle duration of DIFS when a transmission is finished, while non real-time packets have to wait for an idle duration of DIFS+SLOT to decrease the backoff counter after a transmission is finished.

We can still use (1) to compute the collision probability p , although the AIFSs have an effect on the collision probability p . Due to longer AIFS, the average backoff counter for non real-time packets will be $(CW/2+1)$ instead of $CW/2$ and the collision probability p will reduce $2/CW$. For example, when CW equals to 64, the collision probability p only reduces by

3%. So, the AIFS has very little effect on the collision probability p and we can ignore its effect to simplify the analysis. As a result, the average delay D for the system does not change much. The average delay D computed by (4) is still valid under this priority scheme. Our simulation also verifies this fact.

Let τ be the probability that a station transmits its packet in a randomly chosen slot time. Then, the collision probability p is the probability that at least one of the remaining $N-1$ stations also transmits its packet during this randomly chosen slot time (i.e., at least one of the other stations also chooses this slot time to transmit). This yields to

$$p = 1 - (1 - \tau)^{N-1}. \quad (5)$$

As discussed earlier, all the packets have to backoff at least one time. For each packet, the average backoff counter is $CW/2$ when the contention window is CW . Since the collision probability for each packet is the same, the average number of collisions that a real-time packet experiences before it is successfully transmitted is the same as that for a non real-time packet. Whenever a collision occurs, a new backoff is initiated. Thus, the average number of backoffs for a real-time packet is also the same as that for a non real-time packet.

Now we consider the first backoff. To compute the average delay for a real-time packet at this backoff, we first determine how many transmissions occur before the backoff counter of this packet decreases to zero. Suppose at the first backoff, the contention window is CW , then, the average backoff counter of a packet is $CW/2$ and except this packet, there are $N-1$ stations contending for the channel during each slot of this packet's backoff period. As we defined earlier, τ is the probability that a station transmits its packet in a randomly chosen slot time. Thus, the probability that at least one of the $N-1$ stations transmits its packet in each slot of this packet's backoff time is $1 - (1 - \tau)^{N-1}$, which is equal to the collision probability p . Then, the average number of transmissions during $CW/2$ slots period is $p \cdot CW/2$.

For a real-time packet, its average backoff counter is $CW/2$. Similarly, there will be $p \cdot CW/2$ transmissions during its $CW/2$ slots backoff period. In the IFS priority scheme, every time when a transmission is finished, the stations with the real-time packet will be one slot shorter than the stations with the non real-time packet to wait to decrease the backoff counter. Thus, a real-time packet does not backoff $CW/2$ slots compared to the non real-time packets. Actually it only backoffs $CW/2 - p \cdot CW/2 = (1-p) \cdot CW/2$ slots.

For a non real-time packet, it is a little complicated to compute its actual backoff slots. As the average backoff counter for a non real-time packet is also $CW/2$, then the average number of transmissions during this $CW/2$ slots period is $p \cdot CW/2$. Due to other stations' transmission, this packet has to wait for another $(p \cdot CW/2)$ slots period. While during this additional $(p \cdot CW/2)$ slots period, there are $p \cdot (p \cdot CW/2)$ transmissions. Then, this packet has to wait for another $p \cdot (p \cdot CW/2)$ slots period. By repeating this process, we get the actual backoff slots of a non real-time packet as

$$\frac{CW}{2} + p \cdot \frac{CW}{2} + p \cdot p \cdot \frac{CW}{2} + \dots = \frac{1}{1-p} \cdot \frac{CW}{2}. \quad (6)$$

Let $D_{r,i}$ be the average delay for real-time packets and $D_{nr,i}$ be the average delay for non real-time packets at the i th backoff, then we can get

$$D_{nr,i} = \frac{1}{(1-p)^2} D_{r,i}. \quad (7)$$

Similarly, we can analyze the average delay for real-time packets and non real-time packets at i th ($i > 1$) backoff and get

$$D_{nr,i} = \frac{1}{(1-p)^2} D_{r,i}. \quad (8)$$

Let D_r be the average delay for the real-time packets, D_{nr} be the average delay for the non real-time packets. Since the number of backoffs for real-time packets is the same as that for non real-time packets, summing the delay for all the number of backoffs, we have

$$D_{nr} = \sum_i D_{nr,i} = \frac{1}{(1-p)^2} D_r. \quad (9)$$

Since the average delay D for the system can be computed by

$$D = R_r \cdot D_r + (1 - R_r) \cdot D_{nr}. \quad (10)$$

Then, we get D_r from (9) and (10) as

$$D_r = \frac{(1-p)^2}{R_r \cdot (1-p)^2 + (1-R_r)} \cdot D. \quad (11)$$

Replacing D with (4), we get

$$D_r = N \cdot \frac{2-p}{2} \cdot \frac{1-p}{R_r \cdot (1-p)^2 + (1-R_r)} \cdot (T_{DIFS} + T_p + T_{SIFS} + T_{ACK} + \frac{CW_{min}}{N+1} \cdot T_{slot}). \quad (12)$$

Then, we have

$$D_{nr} = N \cdot \frac{2-p}{2(1-p)} \cdot \frac{1}{R_r \cdot (1-p)^2 + (1-R_r)} \cdot (T_{DIFS} + T_p + T_{SIFS} + T_{ACK} + \frac{CW_{min}}{N+1} \cdot T_{slot}). \quad (13)$$

2) CW priority scheme

The CW priority scheme implements service differentiation by setting different CW_{min} to different TC. To avoid more collisions caused by the smaller contention window, we adjust the value of CW_{min} for real-time packets according to the R_r . We let non real-time packets use CW_{min} and real-time packets use $R_r \cdot CW_{min}$ as the minimum contention window respectively.

Although real-time packets have a shorter delay, non real-time packets could suffer from this scheme. Smaller contention window for real-time packets will bring a little more collisions to the system, but it will also bring a much shorter delay for real-time packets. As long as CW_{min} is large enough (e.g., $CW_{min} \geq 64$), the average delay is still the same as the delay without backoff priority. Our simulation results validate this fact and show that even the worst case (i.e., $R_r = 0.5$) in this CW priority scheme, which could bring the most

number of collisions to the system, does not degrade the average delay performance.

Suppose at the first backoff, the contention window of the real-time packets is $R_r \cdot CW$ while the contention window of the non real-time packets is CW . Then, the average backoff counter of the real-time packets is $(R_r \cdot CW)/2$, while the average backoff counter of the non real-time packets is $CW/2$. Therefore, the average delay for the real-time packets is R_r , of the average delay for non real-time packets at this backoff. That is,

$$D_{r,i} = R_r \cdot D_{nr,i}. \quad (14)$$

Since the number of backoffs for real-time packets is the same as that for non real-time packets, and the minimum contention window for real-time packets is the R_r of that for non real-time packets, then the contention window for real-time packets and non real-time packets is doubled at the same time at each instance of backoffs. So the contention window for real-time packets is always the R_r of that for non real-time packets at each instance of backoffs. Similarly, we have

$$D_{r,i} = R_r \cdot D_{nr,i}. \quad (15)$$

Summing the delay at each instance of backoffs, we get

$$D_r = \sum_i D_{r,i} = R_r \cdot D_{nr}. \quad (16)$$

From (10) and (16), we get

$$D_r = \frac{R_r \cdot D}{R_r^2 + 1 - R_r},$$

and

$$D_{nr} = \frac{D}{R_r^2 + 1 - R_r}.$$

We still use (4) to compute the average delay D . Substitute with (4), we have

$$D_r = N \cdot \frac{(2-p)R_r}{2(1-p)(R_r^2 + 1 - R_r)} \cdot (T_{DIFS} + T_p + T_{SIFS} + T_{ACK} + \frac{CW_{min}}{N+1} \cdot T_{slot}), \quad (17)$$

and

$$D_{nr} = N \cdot \frac{2-p}{2(1-p)(R_r^2 + 1 - R_r)} \cdot (T_{DIFS} + T_p + T_{SIFS} + T_{ACK} + \frac{CW_{min}}{N+1} \cdot T_{slot}). \quad (18)$$

V. PROPOSED PRIORITY SCHEME

Although EDCF can provide different QoS to different TCs, it cannot satisfy all the QoS requirements since all the packets still need to contend for the channel. To improve the performance for real-time packets, we propose a priority scheme, called UEDCF. In this scheme, a station can successively use the channel if it generates real-time packets continuously. When a station successfully finishes its transmission, it will check its next packet. If it is a real-time packet, the station will transmit this packet after an idle period

of SIFS. Since other stations can transmit their packets after an idle period of DIFS and SIFS is shorter than DIFS, then only this station can get the channel. Thus, we not only implement the priority for real-time packets, but also reduce the contention time and collisions so that the overall system performance could be improved. To provide fairness among all the stations, we define a variable, fairIndex, as the fairness index. This variable can be assigned a value which is the maximum number of real-time packets that a station can transmit continuously. A larger value means an increased unfairness in the system. We can adjust this value to satisfy the system requirement.

Next, we evaluate our proposed UEDCF scheme. We still assume that at each station, the fraction of the real-time packets is R_r and that of the non real-time packets is $(1-R_r)$. Then, the average number (denoted by n_c) of real-time packets that will be continuously sent after a successful transmission is given as

$$n_c = \sum_{i=1}^{\text{fairIndex}} R_r^i. \quad (19)$$

Let M denote the total number of packets that are successfully transmitted in the system, and M_r denote the number of real-time packets that are additionally, continuously transmitted within these M packets. Then, we have

$$M_r = \frac{n_c}{1+n_c} \cdot M. \quad (20)$$

Excluding these M_r real-time packets not contending for the channel, the remaining $(M-M_r)$ packets (including real-time and non real-time packets) contend for the channel and have the same delay performance. Due to the time occupied by transmission of these M_r packets, $(M-M_r)$ packets have a longer delay than that expressed by (4). Since all the N stations in the system are identical, a station, before its transmission, has to wait for an additional time period which is used for other $(N-1)$ stations to continuously transmit real-time packets. Let T_a denote this period. Then, we can get

$$\begin{aligned} D_{nr} &= T_a + D \\ &= (N-1) \cdot n_c \cdot L + N \cdot \frac{2-p}{2(1-p)} \cdot (T_{\text{DIFS}} + T_p + T_{\text{SIFS}} + T_{\text{ACK}} + \frac{CW_{\text{min}}}{N+1} \cdot T_{\text{slot}}), \end{aligned} \quad (21)$$

where D is given by (4) and L is the delay for the continuously transmit real-time packets. Since these packets need not contend for the channel, the delay L is given by

$$L = T_{\text{SIFS}} + T_p + T_{\text{SIFS}} + T_{\text{ACK}}. \quad (22)$$

Thus, for total $R_r \cdot M$ transmitted real-time packets, M_r packets have the delay of L , and $(R_r \cdot M - M_r)$ packets have the delay of D_{nr} . Therefore, we can get D_r as

$$D_r = \frac{n_c}{R_r \cdot (1+n_c)} \cdot L + \left(1 - \frac{n_c}{R_r \cdot (1+n_c)}\right) \cdot D_{nr}, \quad (23)$$

where D_{nr} and L are given in (21) and (22), respectively.

VI. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we give all the numerical results. The system parameters are given in Table 1.

To validate our analytical results, we have done extensive simulations. The simulator is an event-driven simulator and is implemented in C++. In our simulation, we have tested different values of CW_{min} , the minimum contention window for the real-time packets and non real-time packets. Since the results for different CW_{min} are similar, we only give the results when CW_{min} is equal to 64. To get the average data, we let our simulation run until it successfully transmits 100,000 packets.

Figures 1 and 2 compare the delays of three priority schemes. Figure 1 indicates that our proposed UEDCF priority scheme has the best delay for real-time packets, and Figure 2 shows that our proposed priority scheme does not degrade the delay performance for non real-time packets compared to IEEE 802.11e EDCF. Figure 3 shows the average delay for three schemes. It is observed that UEDCF has the best performance due to the reduced contention time and collisions. Figures 1 and 2 also show that the simulation results match the analytical results very well.

TABLE I. SYSTEM PARAMETERS

Channel bit rate	54 Mbits/sec
Packet length	1728 bytes
Propagation delay	1 μ sec
SLOT	50 μ sec
SIFS	28 μ sec
AIFS (for real-time)	78 μ sec
AIFS (for non real-time)	128 μ sec
ACK	48 μ sec
CW_{min}	64
R_r	0.5
fairIndex	2
m	5

We use the basic scheme (i.e., no IFS priority and no backoff priority) as the base. We find that the improvement in backoff priority scheme is about 33% for the real-time packets delay, no matter how many stations are present in the system. The reason is that the backoff time for real-time packets is always the half of the backoff time for non real-time packets under any condition. IFS priority scheme works better when the number of competing stations is large and it can improve up to 50% for the real-time packets delay. Our proposed priority scheme works best and can improve up to 80% for the real-time packets delay. Furthermore, since our proposed priority scheme can greatly reduce the number of collisions, it can even improve about 30% for the overall system performance.

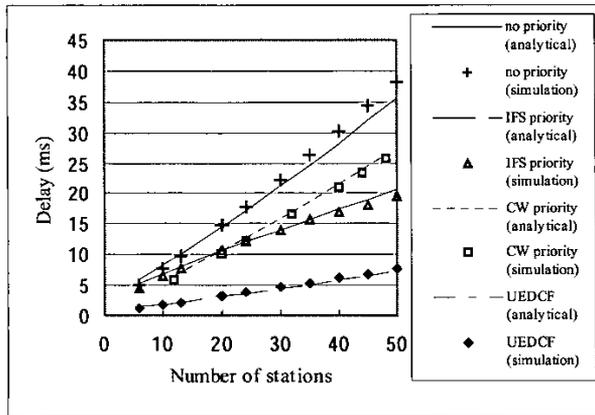


Figure 1. Average delay for real-time packets

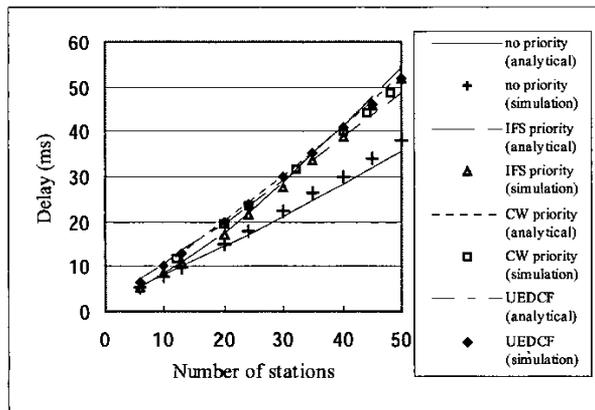


Figure 2. Average delay for non real-time packets

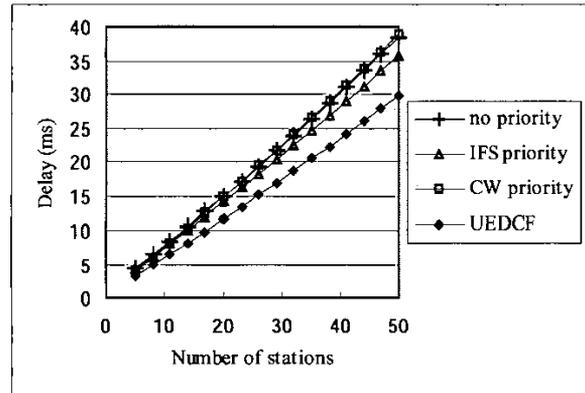


Figure 3. Average delay

VII. CONCLUSIONS

In this paper, we have provided an analytical model to evaluate the performance of IEEE 802.11e EDCF. We have

shown that the delay strongly depends the system parameters, mainly the minimum contention window and Interframe Spaces. Although IEEE 802.11e EDCF can improve the performance for higher priority traffic, it cannot guarantee the QoS requirements since contention for the channel still exists. The IEEE EDCF still needs further investigation before it should become a standard. We proposed a new priority scheme and we observe that our proposed scheme works much better than IEEE 802.11e EDCF. It not only dramatically reduces the delay for real-time traffic, but also improves the overall performance. To validate our analytical results, we have done extensive simulations and it is observed that the simulation results match the analytical results very well.

REFERENCES

- [1] IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, P802.11, November 1999.
- [2] I. Aad and C. Castelluccia, "Differentiation mechanisms for IEEE 802.11," *Proceedings of the IEEE INFOCOM'01*, Anchorage, Alaska, pp. 209-218, April 2001.
- [3] M. Benveniste, G. Chesson, M. Hoeben, A. Singla, H. Teunissen, and M. Wentink, EDCF proposed draft text, IEEE working document 802.11-01/131r1, March 2001.
- [4] M. Barry, A. T. Campbell, and A. Veres, "Distributed Control Algorithms for Service Differentiation in Wireless Packet Networks," *Proceedings of the IEEE INFOCOM 2001*, Anchorage, Alaska, pp. 582-590, April 2001.
- [5] J. Deng and R. S. Chang, "A Priority Scheme for IEEE 802.11 DCF Access Method," *IEICE Transactions on Communications*, Vol. E82-B, No.1 January 1999.
- [6] J. L. Sobrinho, and A. S. Krishnakumar, "Real-Time Traffic over the IEEE 802.11 Medium Access Control Layer," *Bell Labs Technical Journal*, pp. 172-187, Autumn 1996.
- [7] S. Mangold, S. Chio, P. May, O. Klein, G. Hiertz, and L. Stibor, "IEEE 802.11e Wireless LAN for Quality of Service," *Proceedings of European Wireless*, February 2002.
- [8] Q. Qiang, L. Jacob, R. R. Pillai, and B. Prabhakaran, "MAC Protocol Enhancements for QoS Guarantee and Fairness over the IEEE 802.11 Wireless LANs," *Proceedings of International Conference on Computer Communications and Networks*, October 2002.
- [9] L. Kleinrock, and F. A. Tobagi, "Packet switching in Radio Channels: Part I Carrier Sense Multiple Access Modes and Their Throughput Delay Characteristics," *IEEE Transactions on Communications*, Vol. Com-23, No. 12, pp. 1400-1416, 1975.
- [10] J. H. Kim, and J. K. Lee, "Throughput and Packet Delay Analysis of IEEE 802.11 MAC Protocol for Wireless LAN's," *Wireless Personal Communications*, Kluwer academic Publishers, Vol. 11 No. 2, pp.161-183, November 1999.
- [11] H. Tabagi, and L. Kleinrock, "Throughput Analysis for CSMA Systems," *IEEE Transactions on Communications*, Vol. Com-33, No. 7, pp. 627-638, 1985.
- [12] Y. Chen, Q-A Zeng and D. P. Agrawal, "Performance Analysis and Enhancement of IEEE 802.11 MAC Protocol," *Proceedings of International Conference on Telecommunications*, February 2003.
- [13] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, Vol. 18, pp. 535-547, March 2000.
- [14] Y. C. Tay and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol," *ACM/Baltzer Wireless Networks*, Vol. 7, pp. 159-171, March 2001.