Throughput and Delay Analysis of the IEEE 802.11e EDCA Saturation

Juki Wirawan Tantra, Chuan Heng Foh, and Adel Ben Mnaouer
Centre of Multimedia and Network Technology
School of Computer Engineering
Nanyang Technological University
Singapore
Email: jw.tantra@ieee.org, aschfoh@ntu.edu.sg, adelm@pmail.ntu.edu.sg

Abstract— **In this paper, we introduce a simple model for the *enhanced distributed channel access* (EDCA) mechanism under saturation condition. This model captures the operation of the AIFS and contention window differentiation of the EDCA mechanism. Using this model, we analyze the throughput and delay performance of EDCA. The results of our analytical model are then verified using simulations.**

I. INTRODUCTION

The popularity of wireless local area networks (WLANs), especially of IEEE 802.11 standard, has generated much interests on improvement and modeling of the protocol. One of the recent major interests is on the quality of service (QoS) improvement of the IEEE 802.11 standard [1], which is specified by the upcoming IEEE 802.11e standard [2].

The IEEE 802.11 uses two mechanisms for transmission, which are the *distributed coordination function* (DCF) and the *point coordination function* (PCF). DCF uses *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) with binary exponential backoff for channel contention and collision resolution. PCF is an optional contention-free service which uses polling by the centralized point coordinator (PC). Furthermore, DCF employs two techniques for frame transmissions. The default is a two-way handshaking method called *basic access method*. Another technique employs a four-way handshaking method, known as *Request-To-Send/Clear-To-Send* (RTS/CTS).

The IEEE 802.11e standard specifies differentiated service classes in the Medium Access Control (MAC) layer to support the delivery of priority packets such as multimedia data packets. IEEE 802.11e defines *hybrid coordination function* (HCF) for access mechanism, which uses two mechanisms for transmission. They are *enhanced distributed channel access* (EDCA) and *HCF controlled channel access* (HCCA). EDCA is a contention based access mechanism, whereby HCCA is an optional polling based access mechanism.

Many models have been proposed to analyze the throughput and delay of DCF mechanism. Bianchi [3] developed an analytical model to compute the saturation throughput of stations that run DCF mechanism. Wu *et al.* [4] extended the Bianchi's model to include the transmission retry limit that is specified in the standard. Using a similar model, Chatzimisios *et al.* [5] derived the delay of packet transmissions. Foh and Tantra [6] improved the modeling of the backoff freezing mechanism specified by IEEE 802.11 standard first discussed in [7], which is based on the Bianchi's model. Foh and Zukerman [8] analyzed the performance of DCF under statistical traffic.

Some models have also been proposed to analyze the EDCA mechanism. Robinson and Randhawa [9] extended the Bianchi's model to analyze the saturation throughput performance of the EDCA mechanism. This extended model is complex to analyze and extend; hence, it is hard to derive the delay performance from this model. Xiao [10] developed a model to analyze the contention window size differentiation in the EDCA mechanism. However, this model lacks the *Arbitration Inter Frame Space* (AIFS) differentiation and *virtual collision* mechanism specified in the IEEE 802.11e standard.

In this paper, we introduce a simple model for the EDCA mechanism under saturation condition. This model captures the operation of the AIFS and contention window differentiation of the EDCA mechanism. Using this model, we derive the throughput and delay performance of the stations.

This paper is organized as follow. Section II provides a brief summary of the IEEE 802.11 DCF and IEEE 802.11e EDCA operations. Section III describes the developed model for performance analysis of EDCA mechanism. We discuss and verify the results of our analytical model in section IV.

II. MAC PROTOCOLS

This section briefly summarizes the operations of the IEEE 802.11 DCF and the IEEE 802.11e EDCA. For detailed description, readers may refer to [1] and [2].

A. Distributed Coordination Function

DCF employs CSMA/CA MAC protocol with binary exponential backoff. DCF does not use collision detection function as the stations cannot detect collisions by listening their own transmissions; thus, it employs handshaking method, which makes use of positive acknowledgment.

When a station generates a new frame for transmission, it will first monitor the channel activity. If the channel is detected idle for a period of time called *DCF interframe space* (DIFS), the station can transmit immediately. If the channel is busy, the station will defer until the end of transmission and a random backoff interval is selected. The backoff counter is decremented as long as the channel is sensed idle, stopped when channel activity is detected, and reactivated when the channel is sensed idle for more than a DIFS again. The station transmits its frame when the backoff counter reaches zero.

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TABLE I

TYPICAL PARAMETERS FOR VARIOUS ACS.

AC	CW_{min}	CW_{max}	AIFS	Retry Limit
0	32	1024	DIFS + Slot Time	7
1	32	1024	DIFS	7
2	16	256	DIFS	7
3	8	128	DIFS	7

DCF uses a slotted binary exponential backoff technique. The period following an idle DIFS is slotted and the backoff time counter is measured in terms of slot time. The backoff time is uniformly chosen in the range (0,CW-1), where CW is the current contention window. At the first transmission attempt, CW is set equal to the minimum contention window (CW_{min}). After each unsuccessful transmission, CW is doubled until it reaches the maximum contention window (CW_{max}). The IEEE 802.11 standard specifies retransmission limit; if a failed transmission is encountered after the retransmission limit, the frame will be dropped.

When the destination station successfully receives a frame, it will transmit an acknowledgment frame (ACK) after a *short interframe space* (SIFS). If the sender does not receive the ACK within a specified ACK timeout, or it detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the previous backoff rules.

B. Enhanced Distributed Channel Access

EDCA is specified to provide QoS support on IEEE 802.11 WLANs. It supports up to four access categories (AC), from the lowest priority service class, AC$_0$, to the highest priority service class, AC$_3$. EDCA differentiates service classes through three mechanisms: contention window size, AIFS, and transmission opportunity (TXOP) limit differentiations.

Stations that use smaller CW_{min} and CW_{max} receive higher QoS than the other stations as their channel access delays are generally shorter. In EDCA, high priority service class uses smaller CW_{min} and CW_{max} to improve the QoS received by the higher priority classes.

In EDCA, AIFS is used instead of DIFS, where AIFS$\geq$DIFS. Each service class can use different AIFS value to differentiate the QoS received by the service class. Stations that use lower AIFS encounter fewer collisions and count down the backoff counter faster than the other stations; hence, they receive better QoS.

EDCA also allows stations to transmit multiple frames without contending again, known as contention free bursting (CFB). CFB is limited by the TXOP limit specified for each service class. Longer limit means that the service class can transmit more frames; hence, it receives better QoS. In this paper, we consider saturation condition; thus, CFB has little effect on the operations of the system. Therefore, we focus on contention window and AIFS differentiation in this paper.

In EDCA, each station implements a queue for each AC. Each queue has its own QoS parameters and backoff counter. A collision within a station is handled virtually, whereby the frame from the highest priority queue involved in the collision is chosen and transmitted to the access medium. This mechanism is known as *virtual collision*.

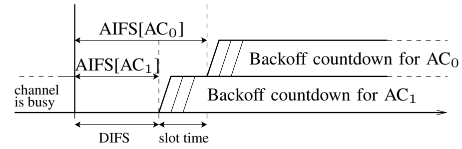

Fig. 1. Timing of the EDCA mechanism.

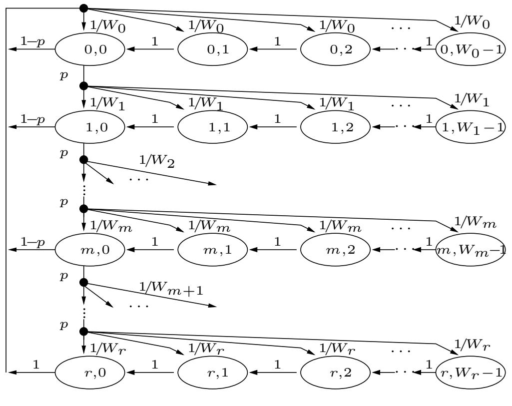

Fig. 2. Markov Chain model for AC$_1$, AC$_2$, AC$_3$.

Table I shows some typical parameters for various ACs in EDCA. These parameters are based on the IEEE 802.11b [11] parameters. We will use these parameters in the subsequent analysis. Fig. 1 shows the timing relations of AC$_0$ and AC$_1$ stations.

III. ANALYTICAL MODEL

We model the backoff operation of each station with a Markov Chain. Our approach is similar to that of [3]. We use the parameters in Table I for the analysis. In this section, we assume that each station only implements one queue of the four ACs in EDCA. Virtual collision is handled separately in section IV-D.

To capture the operation of AIFS differentiation, we use different types of chains for different AIFS values. Two different types of chains are required according to parameters shown in Table I. Fig. 2 shows the Markov Chain model for stations implementing AC$_1$ to AC$_3$, hereafter we refer as *chain A*. This model is the Bianchi's model with the addition of frame retransmission limit, which is first proposed by Wu et al. [4]. The state $\{i,j\}$ in *chain A* corresponds to the ith backoff stage of a station and that station has j as its backoff counter. The variable i ranges from 0 as the first backoff stage to r the retransmission limit. The value j ranges from 0 to W_i-1, where W_i is the backoff window of stage i; the backoff window W_i is given by

$$W_i = \begin{cases} 2^i \cdot CW_{min}, & 0 \leq i \leq m \\ 2^m \cdot CW_{min}, & m < i \leq r. \end{cases} \quad (1)$$

The conditional collision probability p is the probability that a frame encounters a collision when it is transmitted. Similar with [3], we assume that the probability p is constant and independent of the number of retransmission.

The Markov Chain model for stations implementing AC$_0$ is shown in Fig. 3. We will refer this model as *chain B*. AC$_0$

stations need to wait for a slot time longer than the other stations when a transmission occurs. This waiting is modeled by extra states, states $\{i, j, 1\}$. These states have loop transitions, which model the backoff counter freezing by AC_0 stations when transmissions by higher priority stations occur before the AIFS for AC_0. States $\{i, j, 0\}$ model the situation after the AIFS period for AC_0; thus, the AC_0 stations have restarted their backoff counters. The probabilities q_1 and q_2 are the probabilities that a slot time does not contain a transmission by non-AC_0 stations and by any stations respectively. When a transmission occurs during backoff counter countdown of an AC_0 station, the station will freeze its backoff counter, and the state is moved to state $\{i, j, 1\}$. This transmission occurs with the probability $1 - q_2$. The AC_0 stations will freeze their backoff counter until an AIFS period is encountered, which means that there is no higher priority stations transmit in that period; hence, the backoff counter is restarted with the probability q_1.

Let $\alpha_{i,j}$ be the stationary distribution of *chain A*. Owing to the chain regularities, we have

$$\begin{aligned} \alpha_{i,0} &= p \cdot \alpha_{i-1,0}, && 0 < i \le r \\ \alpha_{i,j} &= \frac{W_i - j}{W_i} \cdot \alpha_{i,0}, && 0 \le i \le r, 0 < j < W_i. \end{aligned} \tag{2}$$

Imposing the normalization condition, $\sum_{i,j} \alpha_{i,j} = 1$, we get

$$\alpha_{0,0} = \begin{cases} \dfrac{\xi}{\iota_r + \kappa} & r \le m, \\ \dfrac{\xi}{\iota_m + \kappa + \nu} & r > m, \end{cases} \tag{3}$$

where ξ, ι, κ, and ν are given by

$$\begin{aligned} \xi &= 2(1-2p)(1-p) \\ \iota_r &= W(1-(2p)^{r+1})(1-p) \\ \iota_m &= W(1-(2p)^{m+1})(1-p) \\ \kappa &= (1-2p)(1-p^{r+1}) \\ \nu &= W 2^m p^{m+1}(1-2p)(1-p^{r-m}). \end{aligned} \tag{4}$$

Similarly for AC_0, let $\beta_{i,j,k}$ be the stationary distribution of *chain B*. Owing to the chain regularities, we have

$$\begin{aligned} \beta_{i,0,0} &= p \cdot \beta_{i-1,0,0}, && 0 < i \le r \\ \beta_{i,j,0} &= \frac{W_i - j}{W_i} \cdot \beta_{i,0,0}, && 0 \le i \le r, 0 < j < W_i \\ \beta_{i,j,1} &= \frac{W_i - j - (W_i - j - 1)q_2}{W_i q_1} \cdot \beta_{i,0,0}, \\ & && 0 \le i \le r, 0 < j < W_i. \end{aligned} \tag{5}$$

With normalization condition $\sum_{i,j,k} \beta_{i,j,k} = 1$, we obtain

$$\beta_{0,0,0} = \begin{cases} \dfrac{q_1 \xi}{(1+q_1-q_2)\iota_r + (1+q_1+q_2)\kappa} & r \le m, \\ \dfrac{q_1 \xi}{(1+q_1-q_2)(\iota_m+\nu) + (1+q_1+q_2)\kappa} & r > m, \end{cases} \tag{6}$$

where ξ, ι, κ, and ν are given by (4).

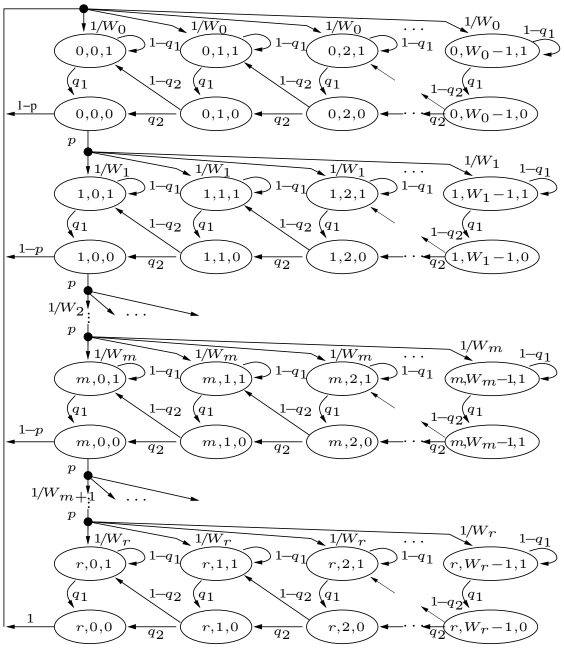

Fig. 3. Markov Chain model for AC_0.

The probabilities τ_i that a station of AC_i transmits in a slot are given by

$$\tau_i = \begin{cases} \dfrac{\sum_{i=0}^{r} \beta_{i,0,0}}{P_I} = \dfrac{(1-p^{r+1})\beta_{0,0,0}}{(1-p)P_I}, & i = 0 \\ \displaystyle\sum_{i=0}^{r} \alpha_{i,0} = \frac{1-p^{r+1}}{1-p}\alpha_{0,0}, & i = 1,2,3 \end{cases} \tag{7}$$

The probability τ_0 is conditioned on the probability that the previous slot is an idle slot as transmissions by AC_0 stations cannot occur after a busy slot (AC_0 stations need to wait for an extra slot time compared with the other stations before they have the chance to transmit). The probability P_I that a slot is idle is

$$P_I = q_1 P_B + q_2 P_I = \frac{q_1}{1+q_1-q_2}, \tag{8}$$

where the probability P_B that a slot is busy given by $P_B = 1 - P_I$.

The probabilities τ_i also depend on the collision probability p_i that a packet from an AC_i station encounters a collision, which is given by

$$p_i = \begin{cases} 1 - (1-\tau_i)^{n_i - 1} \displaystyle\prod_{x \ne i} (1-\tau_x)^{n_x}, & i = 0 \\ (1 - (1-\tau_i)^{n_i - 1} \displaystyle\prod_{x \ne 0,i} (1-\tau_x)^{n_x}) P_B \\ \quad + (1 - (1-\tau_i)^{n_i - 1} \displaystyle\prod_{x \ne i} (1-\tau_x)^{n_x}) P_I \\ \qquad i = 1,2,3. \end{cases} \tag{9}$$

The probabilities p_1, p_2, and p_3 are conditioned on whether the previous slot is a busy slot or an idle slot. This is because the number of stations that can compete on the two cases is different. If the previous slot is a busy slot, only stations of

AC$_1$, AC$_2$, and AC$_3$ can transmit on the current slot as stations of AC$_0$ need to wait for an extra slot time for a chance to transmit. The probabilities q_1 and q_2 that a transmission does not occur in a slot during an AIFS period and during other period respectively are

$$
\begin{aligned}
q_1 &= \prod_{i=1}^{3}(1-\tau_i)^{n_i}, \\
q_2 &= \prod_{i=0}^{3}(1-\tau_i)^{n_i}.
\end{aligned}
\tag{10}
$$

Equations (7)-(10) form a set of non-linear equations that can be computed numerically.

The probabilities P_{Si} that a slot time contains a successful transmission by a station of class AC$_i$ are given by

$$
P_{Si} = \begin{cases}
n_i\tau_i(1-\tau_i)^{n_i-1}\prod_{x\neq i}(1-\tau_x)^{n_x}, & i=0 \\
n_i\tau_i(1-\tau_i)^{n_i-1}\prod_{x\neq 0,i}(1-\tau_x)^{n_x}P_B & \\
\quad + n_i\tau_i(1-\tau_i)^{n_i-1}\prod_{x\neq i}(1-\tau_x)^{n_x}P_I, & \\
 & i=1,2,3.
\end{cases}
\tag{11}
$$

The probabilities P_{S1}, P_{S2}, and P_{S3} are also conditioned on whether the previous slot is a busy slot or an idle slot due to a similar reason with that of the probabilities p_1, p_2, and p_3. The probability P_C that a slot time contains a collision is $P_C = 1 - P_I - P_S$, where $P_S = \sum_{i=0}^{3} P_{Si}$.

IV. RESULTS AND DISCUSSIONS

A. Saturation throughput

The saturation throughput is given by

$$
S = \frac{P_S E[P]}{E[ST]}, \tag{12}
$$

where P_S is the probability that a slot contains a successful transmission given by (11), $E[P]$ is the average length of frame payload, and $E[ST]$ is the average length of a slot. The value $E[ST]$ is computed by

$$
E[ST] = P_I\sigma + P_S T_S + P_C T_C, \tag{13}
$$

where σ is the length of a slot time, T_S is average length of successful transmission, and T_C is the average length of collision. The value T_S and T_C are given by

$$
\begin{aligned}
T_S^{bas} &= H + E[P] + SIFS + \delta + ACK + AIFS_{min} + \delta, \\
T_C^{bas} &= H + E[P^*] + AIFS_{min} + \delta, \\
T_S^{rts} &= RTS + SIFS + \delta + CTS + SIFS + \delta + H \\
&\quad + E[P] + SIFS + \delta + ACK + AIFS_{min} + \delta, \\
T_C^{rts} &= RTS + AIFS_{min} + \delta
\end{aligned}
\tag{14}
$$

for basic access method and RTS/CTS method respectively.

Saturation throughput of the four ACs are shown in Fig. 4 for basic access method and RTS/CTS method. We use the parameters of IEEE 802.11b standard [11] for both the analysis and simulations. The figure shows a close match between analytical and simulation results. Our simulation follows the assumptions in [3]. The results indicate that EDCA can provide rate differentiation among stations of various ACs.

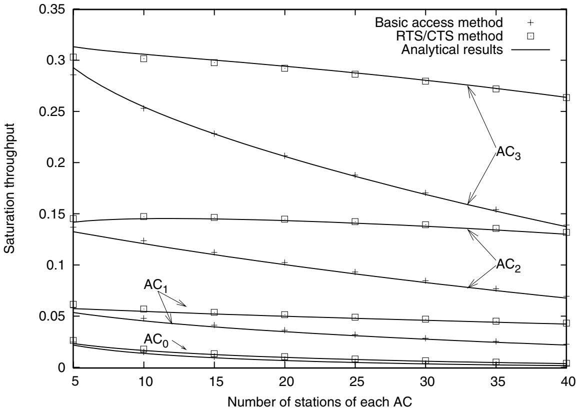

Fig. 4. Saturation throughput for basic access and RTS/CTS methods.

B. Packet dropping probability

A frame will be dropped by a station when the station is in the last backoff stage and the frame encounters a collision. This frame dropping occurs with probability p_{drop}, which is the probability that a frame encounters $r+1$ collisions. The probability p_{drop} is given by

$$
p_{drop} = p^{r+1}. \tag{15}
$$

C. Average packet delay

We use an approach similar to [5] to derive the average delay of the successful packet transmissions. The average packet delay $E[D]$ for packets of class AC$_1$, AC$_2$, and AC$_3$ is given by

$$
E[D] = E[X] \cdot E[ST], \tag{16}
$$

where $E[X]$ is the average number of slots that a packet encounters before it is successfully transmitted and $E[ST]$ is the average length of a slot given by (13). The average number of slot, $E[X]$, is given by

$$
E[X] = \sum_{i=0}^{r}\left[\frac{(p^i - p^{r+1})\frac{W_i+1}{2}}{1-p^{r+1}}\right]. \tag{17}
$$

$E[X]$ is conditioned on successful transmission of the frame, which occurs with probability $1-p^{r+1}$, as dropped frames are not included in the delay calculation. The probability $\frac{p^i-p^{r+1}}{1-p^{r+1}}$ is the probability that a frame reach ith stage of the backoff.

Fig. 5 shows the average delay of AC$_1$ to AC$_3$ for basic access method and RTS/CTS method. The evidence of delay differentiation by EDCA is shown in the figure.

D. Virtual Collision

Consider the case where each station runs four queues where each queue corresponds to an AC. With virtual collision, when two or more queues of a station have backoff counters of zero,

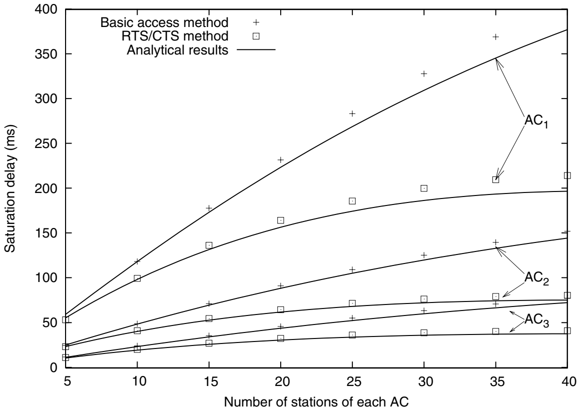

Fig. 5. Saturation delay for basic access and RTS/CTS methods.

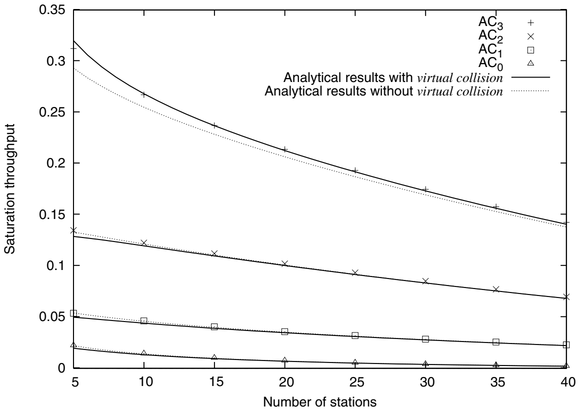

Fig. 6. Saturation throughput with *virtual collision* for basic access method.

the highest priority queue is favored and given the chance to access the medium; hence, the collision is handled virtually within the station itself. The lower priority queues still see the collision, and they will increase their backoff stages and choose other backoff counters.

We use the same approach as in the previous scenario for virtual collision case with some notable differences. Firstly, as each station now has four queues, we use a Markov Chain to model each queue instead of each station. Secondly, virtual collision changes the collision probability seen by each queue as higher priority queues will not see the collision with the lower priority queues of the same station. The collision probability p_i of AC$_i$ is now given by

$$p_i = \begin{cases} 1-(1-\tau_i)^{n_i-1}\prod_{x\neq i}(1-\tau_x)^{n_x}, & i=0 \\ (1-\prod_{x\leq i\ ,\ x\neq 0}(1-\tau_x)^{n_x-1}\prod_{x>i}(1-\tau_x)^{n_x})P_B & \\ \quad +(1-\prod_{x\leq i}(1-\tau_x)^{n_x-1}\prod_{x>i}(1-\tau_x)^{n_x})P_I, & \\ \qquad\qquad\qquad i=1,2,3. & \end{cases} \tag{18}$$

With the above modification, we show the saturation throughput of the four ACs with virtual collision in Fig. 6. Virtual collision mechanism favors higher priority ACs; hence, higher priority ACs encounter less collisions compared with the previous case (Fig. 4) allowing the slight increase of the saturation throughput. This comparison shows that virtual collision has little effect on the performance under saturation condition, especially with high number of stations. Intuitively, virtual collision only reduces the collisions within queues in one station, which is small compared with the collisions with the other stations. For example, consider five stations and each runs four queues, the frames from the highest priority queue of a station will not collide with frames from the other three queues within itself, but they may still collide with the frames from the queues of other stations with a total of sixteen queues. The probability of collisions within oneself is not significant compared with that of the collisions with sixteen queues from other stations; hence, the effect of virtual collision is small in this case.

V. CONCLUSION

In this paper, we have introduced a simple model of the EDCA mechanism under saturation condition. This model captures the operation of the AIFS and contention window differentiation of the EDCA mechanism. Using this model, we analyzed the throughput and delay performance of the EDCA mechanism. Furthermore, we have also analyzed the mechanism of virtual collision. The results of our analytical model are then verified by simulations, which show the accuracy or our model.

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