Performance Analysis of IEEE 802.11e Contention-Based Channel Access

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***Abstract*—The new standard IEEE 802.11e is specified to support quality-of-service in wireless local area networks. A comprehensive study of the performance of enhanced distributed channel access (EDCA), the fundamental medium access control mechanism in IEEE 802.11e, is reported in this paper. We present our development of an analytical model, in which most new features of the EDCA such as virtual collision, different arbitration interframe space (AIFS), and different contention window are taken into account. Based on the model, we analyze the throughput performance of differentiated service traffic and propose a recursive method capable of calculating the mean access delay. Service differentiation functionality and effectiveness of the EDCA are investigated through extensive numerical and simulation results. The model and the analysis provide an in-depth understanding and insights into the protocol and the effects of different parameters on the performance.**

***Index Terms*—Enhanced distributed channel access (EDCA), IEEE 802.11e, performance analysis, saturation conditions, wireless local area network (WLAN).**

I. Introduction

In RECENT years, we have witnessed an amazingly rapid evolution in wireless local area networks (WLANs). Due to the low cost, ease of deployment, and mobility support, IEEE 802.11 WLANs have been used so widely that they become the dominating WLAN technology. This is mainly because the technology is reaching an unprecedented maturity in regard to providing ever-growing bitrates [1]–[5]; however, it cannot fulfill the ever-increasing demand for quality-of-service (QoS) support from the increasingly popular multimedia applications. Consequently, a new standard IEEE 802.11e is specified [6]–[8]. It aims to support QoS by providing differentiated classes of service in the medium access control (MAC) layer and to enhance the ability of all physical layers so that they can deliver time-critical multimedia traffic, in addition to traditional data packets.

In IEEE 802.11e, a new MAC access method named hybrid coordination function (HCF) is introduced [6]–[8]. The HCF consists of two parts. One is HCF contention-based channel access mechanism, also named enhanced distributed channel access (EDCA).[1] The other one is HCF controlled channel access (HCCA). The EDCA is the fundamental and mandatory mechanism of IEEE 802.11e, while HCCA is optional and requires centralized polling and scheduling algorithms to allocate the resources. Until recently, there have been some articles that introduce the forthcoming protocol and EDCA, with only some simulation results [7]–[10]. This paper aims at providing a complete analytical performance model and analysis for the EDCA.

Some previous investigations into protocol performance have been conducted for the distributed coordination function (DCF), the basic MAC access mechanism for IEEE 802.11 WLANs without QoS. In [11], the authors present an analytical model of the DCF from the point of view of collision avoidance (CA) with a backoff procedure and capture effect. In [12]–[14], the backoff time was assumed to follow a geometric distribution with a parameter related to the average value of all the backoff times. Theoretical and simulation results were obtained and some improvements were also proposed. In [15], the number of transmissions per packet was assumed geometrically distributed, and with an average backoff time equal to half of the contention window (CW) size. In [16] and [17], Bianchi proposed an analytical model, using a discrete time Markov chain to obtain an effective and accurate analysis for the DCF. In [18], the same method was employed in the context of mobile ad hoc networks. Based on Bianchi's model, in [19] and [20], similar methods for computing the mean access delay were proposed.

All of these models are applied to the analysis of the legacy DCF. However, they do not capture the new characteristics of IEEE 802.11e EDCA, viz., virtual collisions, different arbitration interframe space (AIFS) and different CW for multiclass access categories (ACs). To better analyze the EDCA and provide an in-depth understanding of the new features, we fully extend the original model proposed by Bianchi for DCF [16], [17], and develop a three dimensional discrete time Markov chain model. The newly developed model reflects the backoff and access procedures accurately, by taking into account the backoff timer freeze that occurs when a station is deferring, and different AIFS and CW parameters, as well as the virtual collision policy. The third dimension in the model is a vitally necessary component used to analyze the differentiation of multiclass ACs with different AIFSs, which significantly affects the transmission and

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[1]Previously, before Draft4.3, it is named enhanced distributed coordination function (EDCF).

collision probabilities as well as the access delay. Moreover, we have taken into account the difference between the countdown procedure of the EDCA and the legacy DCF, and the retransmission limit, which is omitted in all previous models [16]–[20]. This makes the model more accurate in regard to the protocol specification. The analysis of throughput performance is valid for both request-to-send/clear-to-send (RTS/CTS) and basic access modes. In addition, we propose a recursive method to calculate the mean access delay for both of them.

The remainder of this paper is organized as follows. The DCF and IEEE 802.11e EDCA are briefly reviewed in Section II. The proposed analytical system model is presented in Section III. Section IV provides throughput and delay analysis. Numerical and simulation results are given and discussed in Section V. Finally, we draw our conclusions in Section VI.

II. IEEE 802.11E CONTENTION-BASED CHANNEL ACCESS

A. Distributed Coordination Function (DCF)

DCF is the basic MAC mechanism for IEEE 802.11 WLANs. It is based on carrier sense multiple access with collision avoidance (CSMA/CA). Before a station starts a transmission, it must sense the channel idle for a duration, called DCF interframe space (DIFS), plus an additional backoff time. Only when the channel remains idle during all this time can the station initiate the transmission. The backoff time is an integer multiple of a basic time slot, drawn randomly between zero and the so-called CW. For each successfully received frame, the receiving station immediately replies with an acknowledgment frame (ACK). After an unsuccessful transmission attempt, the CW is doubled and another attempt with backoff is performed. Stations that are “beaten to channel access” by another station defer from channel access and freeze their backoff counters, and resume the frozen timers after sensing the channel idle again for DIFS [1].

An optional mechanism named RTS/CTS is also defined in the DCF. This is used to mitigate the effect of long data frame collisions. Before transmitting a data frame, a station transmits a short RTS frame, and the destination station replies to it with a CTS frame. Other stations that overhear either an RTS or a CTS or both, set their network allocation vector (NAV) to the value carried by the so-called duration field of the RTS/CTS frame. The NAV value indicates the duration of the ongoing transmission. After setting the NAV value, the stations defer for the whole duration of the NAV period. Between any two consecutive frames in the sequence of RTS-CTS-Data-ACK, a short interframe space (SIFS) gives transceivers enough time to turn around and ensure that new attempts with longer IFS (i.e., DIFS) cannot preempt the ongoing transmissions [1].

B. Enhanced Distributed Channel Access (EDCA)

EDCA is designed to enhance the DCF mechanism and to provide a distributed access method that can support service differentiation among classes of traffic. It can provide up to four ACs. EDCA assigns smaller CWs to ACs with higher priorities to bias the successful transmission probability in favor of high-priority ACs in a statistical sense. Indeed, the initial CW

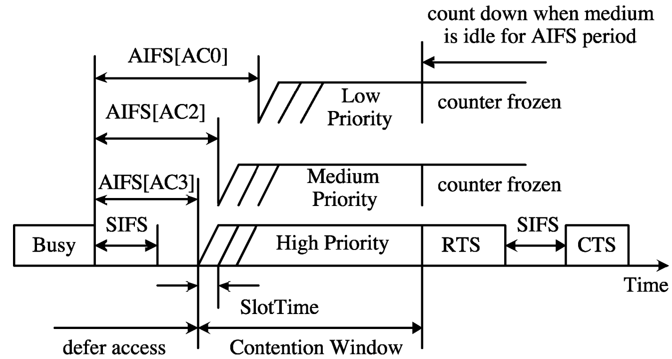


Fig. 1. IEEE 802.11e EDCA mechanism parameters.

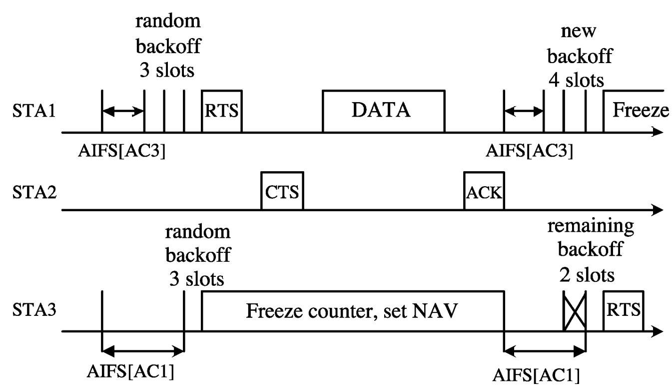


Fig. 2. IEEE 802.11e EDCA channel access procedure.

size $(\mathrm{CW}_{\min})$ can be set differently for different priority ACs, yielding higher priority ACs with smaller $\mathrm{CW}_{\min}$. To achieve differentiation, instead of using fixed DIFS as in the DCF, an AIFS is applied, where the AIFS for a given AC is determined by the following equation:

$$\mathrm{AIFS} = \mathrm{SIFS} + \mathrm{AIFSN} \times \mathrm{aSlotTime}$$

where AIFSN is AIFS Number and determined by the AC and physical settings, and aSlotTime is the duration of a time slot. The AC with the smallest AIFS has the highest priority. Figs. 1 and 2 illustrate these EDCA parameters and the access procedure, respectively.

In the EDCA, both the physical carrier sensing and the virtual sensing methods are similar to those in the DCF. However, there is a major difference in the countdown procedure when the medium is determined to be idle. In the EDCA, after the AIFS period, the backoff counter decreases by one at the beginning of the last slot of the AIFS (shown as the crossed time slot in Fig. 2), while in the DCF, this is done at the beginning of the first time slot interval following the DIFS period [6]–[8].

For a given station, traffic of different ACs are buffered in different queues as shown in Fig. 3. Each AC within a station behaves like a virtual station: it contends for access to the medium and independently starts its backoff after sensing the medium idle for at least AIFS period. When a collision occurs among different ACs within the same station, the higher priority AC is granted the opportunity for physical transmission, while the lower priority AC suffers from a virtual collision, which is similar to a real collision outside the station [6]–[8].

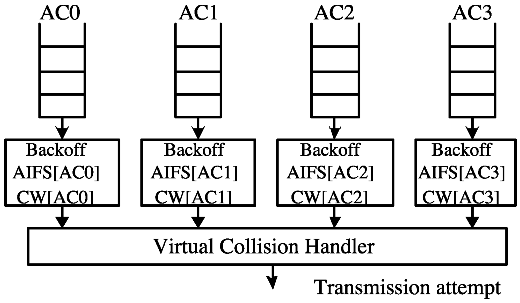


Fig. 3. ACs and virtual collision.

IEEE 802.11e also defines a transmission opportunity (TXOP) limit as the interval of time during which a particular station has the right to initiate transmissions. During an EDCA TXOP, a station may be allowed to transmit multiple data frames from the same AC with a SIFS gap between an ACK and the subsequent data frame [6]–[8]. This is also referred to as contention free burst (CFB). In this paper, for simplicity, we only investigate the situation where a station transmits one data frame per TXOP transmission round.

III. Analytical Model

In this section, we present the proposed analytical model for the EDCA in infrastructure WLAN's mode. In the following, we assume a fixed number of stations (M). Each station has multiple ACs, and each AC always has a packet to transmit. This means the analysis is conducted under saturation conditions. We also assume an ideal channel environment without errors, nor capture effects.

A. Discrete Time Markov Chain Model

In the model, time is considered to be slotted and each state represents an AC in a time slot. At the end of each time slot an event that triggers a transition to another state occurs [22]. Note that this state transition diagram is for one AC per station, rather than for a station as in those original models [16]–[20]. This is because each AC within a station behaves like a virtual station, and invokes its own backoff procedure individually. As a result, we can account for both real and virtual collisions as well as for the different AIFSs.

An omission from all the original models [16]–[20] is the retransmission limitation, defined in [1] and [6]. Let m and h denote the maximum number of retransmission using different CW and the largest CW $(\mathrm{CW}_{\max})$, respectively. If after $m+h$ retries, the AC still cannot access the medium successfully, then the packet is discarded, in other words, $m+h$ is the retry limit.

Let $s(t)$ be the stochastic process representing the backoff stage j at time t, where $0 \le j \le m+h$. Let $b(t)$ be the stochastic process that denotes the value of the backoff counter for a given AC at time t, and the value of the backoff counter is uniformly drawn from $[0, W_j]$, where W_j depends on the retransmission backoff stage j and satisfies $W_{j+1} = 2W_j + 1$. The newly introduced third dimension, $v(t)$, indicates the remaining time during either the frozen, transmission, or collision period.

The three-dimension process $(s(t),\ b(t),\ v(t))$ is a discrete time Markov chain under the assumption that p_i (the collision probability of ACi) and p_b (the channel busy probability) are independent of the backoff procedure. The probability p_i consists of two parts: the external collision probability caused by collisions with other transmissions from other stations, and the internal collision caused by virtual collisions with higher ACs within the same station.

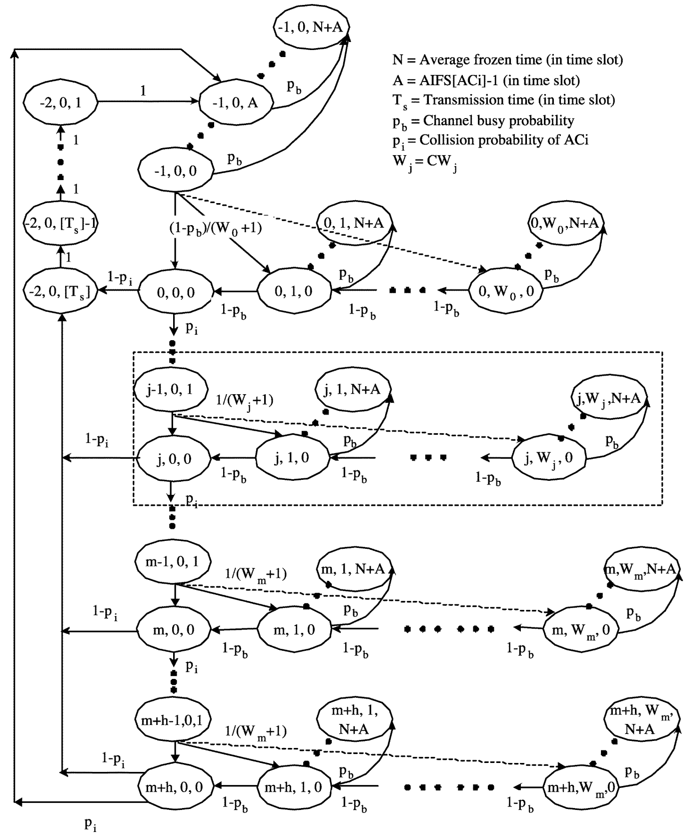


Fig. 4. Transition diagram of discrete time Markov chain model for one AC per station.

At time t, the state of each AC is fully determined by (j, k, d), where j denotes the retransmission backoff stage, $j = 0, 1, \ldots, m+h$ ($j = -2$ and $j = -1$ represent special states which we explain later); k denotes the backoff counter and takes values from $[0, W_j]$; and d indicates either 1) the remaining frozen time (during the deference) before the backoff counter is reactivated for states (j, k, d) with $k \ge 1$, 2) the remaining time for transmission for states $(-2, 0, d)$, or 3) the remaining time for collision period for states $(j, 0, d)$ with $d \ge 1$. The Markov chain is shown in Fig. 4, with a zoom-in of the dashed line box of Fig. 4 shown in detail in Fig. 5.

Without loss of generality, Fig. 5 assumes AIFS takes four time slots (i.e., $A = 3$). Assume RTS/CTS being used, let us consider the possible transition for a targeted AC of a given station in state $(j, 1, 0)$.

In state $(j, 1, 0)$, the packet of this target AC has suffered j collisions and is undergoing the jth backoff for retransmission (as indicated by the first component of the state). Its backoff counter is equal to 1 (as indicated by the second component of the state) and it is in the countdown procedure (i.e., the counter is not frozen, as indicated by the third component of the state).

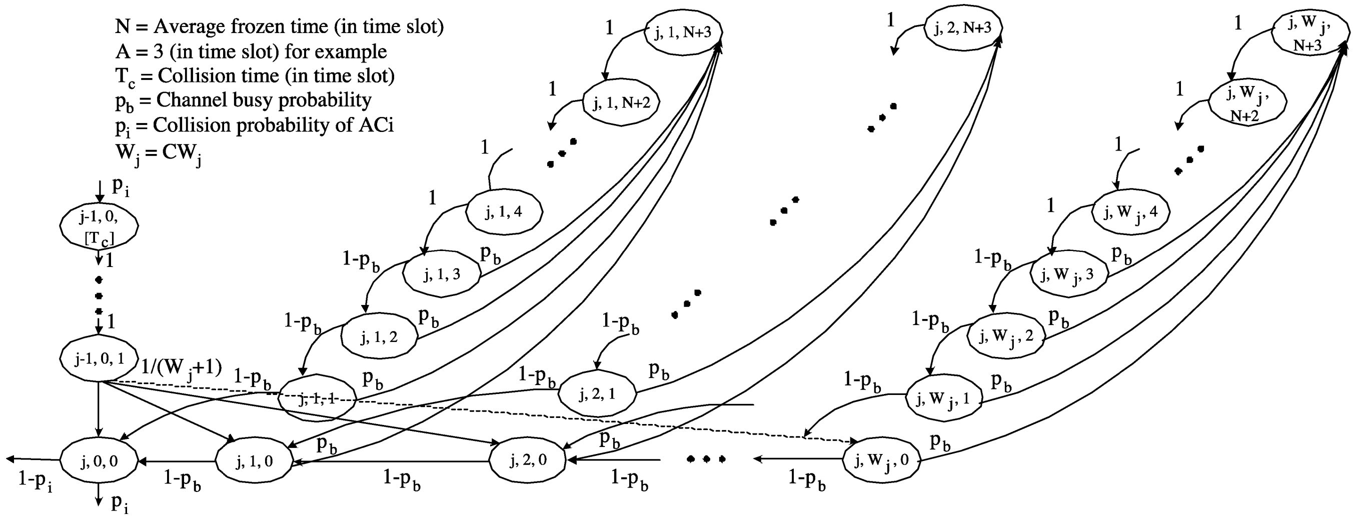


Fig. 5. Transition diagram of one detailed backoff stage.

In this state, if the target AC senses the channel busy, it freezes its backoff counter and starts deferring. This is a transition to state $(j, 1, N+3)$. The value $N+3$ indicates that there are $N+3$ time slots left before the counter can be reactivated, and N is the nearest integer to the frozen time in the time slot unit. During the frozen period, time decreases by one per time slot with probability 1. The transition of the chain to state $(j, 1, 3)$ means that the frozen period has elapsed and the deference period is finished. Then, the station needs to monitor the channel for idleness until the end of the AIFS interval which in this case, is four time slots. If, at the end of the second last time slot, state $(j, 1, 1)$, the channel is still idle, this AC's backoff counter is reactivated and decreases by one. This leads the chain from $(j, 1, 1)$ to state $(j, 0, 0)$. However, if a higher priority AC within the same station, or an AC in another station succeeds again before the target AC finishes the AIFS countdown, then the AC determines the medium busy and freezes its counter again. This is reflected by the transitions from state $(j, 1, d)$, $d = 1, 2, 3$, back to state $(j, 1, N+3)$.

The target AC has to go through the deference procedure again until it reenables its counter and goes to state $(j, 0, 0)$ to access the channel. If no higher priority AC within the same station and no AC in another station, tries to transmit packet at the same time, the target AC's packet is delivered successfully. Some time is required for this transmission and let states $(-2, 0, d)$, $d = 1, 2, \ldots, \lceil T_s \rceil$ represent the successful transmission period, where T_s is the successful transmission time in time slot unit ($\lceil T_s \rceil$ is the smallest integer larger than T_s). However, if there is a collision, before a new backoff is invoked, some time (timeout) will elapse before the station infers the collision. This duration is also divided into time slots and denoted by states $(j, 0, d)$, $d = 1, 2, \ldots, \lceil T_c \rceil$, where Tc is the collision time. The reasoning of N, T_s, and T_c are discussed in Section IV.

After a successful transmission, if during the post-AIFS period the channel is always idle, the AC enters the first backoff stage; if the channel is sensed busy at any time during the AIFS period, the AC freezes again (with the backoff counter equal to zero), and waits until the transmission finishes. States $(-1, 0, d)$, $d = 0, 1, \ldots, N+A$ denote the procedure before the AC enters its first backoff stage.

B. Transition Probabilities

All the transition probabilities in this model are described as follows.

1) For states $(-2, 0, d)$, $d = 1, 2, \ldots, \lceil T_s \rceil$, during the transmission, time progresses by one for each slot

$$P\{(-2, 0, d-1)|(-2, 0, d)\} = 1, \quad 2 \le d \le \lceil T_s \rceil.$$

After a successful transmission, a new packet is scheduled for transmission

$$P\{(-1, 0, A)|(-2, 0, 1)\} = 1.$$

2) For states $(j, 0, 0)$, $j = 0, 1, \ldots, m+h$, when the backoff counter is zero, if no other AC tries to transmit at the same time, the transmission is successful

$$P\{(-2, 0, \lceil T_s \rceil)\,|(j, 0, 0)\} = 1 - p_i, \quad 0 \le j \le m+h.$$

Once a transmission attempt encounters a collision, the AC enters the collision period

$$P\{(j, 0, \lceil T_c \rceil)\,|(j, 0, 0)\} = p_i, \quad 0 \le j \le m+h-1.$$

If $m+h$ retries have been exhausted, the current packet is discarded and the AC starts to handle a new packet

$$P\{(-1, 0, A)|(m+h, 0, 0)\} = p_i.$$

3) For states $(j, 0, d)$, $j = 0, 1, \ldots, m+h-1$ and $d \ge 1$, when there is a collision, some time is needed for the AC to infer the collision (determined by *ACK_Timeout* or *CTS_Timeout*). During such collision period, time progresses by one for each slot

$$P\{(j, 0, d-1)|(j, 0, d)\} = 1, \; 0 \le j \le m+h, \; 2 \le d \le \lceil T_c \rceil.$$

After inferring the collision, the AC doubles the CW size except when it is already using the $\mathrm{CW}_{\max}$, and chooses a random number uniformly distributed in $[0, W_{j+1}]$ and enters the next backoff stage

$$P\{(j+1,k,0)|(j,0,1)\} = \frac{1}{W_{j+1}+1} \quad 0 \le k \le W_{j+1},\ 0 \le j \le m+h-1.$$

4) For states $(j,k,0)$, $j = 0,1,\ldots,m+h$ and $k \ge 1$, the backoff counter decreases by one if the AC senses the channel idle when it is not frozen

$$P\{(j,k-1,0)|(j,k,0)\} = 1-p_b,\ 1 \le k \le W_j,\ 0 \le j \le m+h.$$

The backoff counter is frozen when the AC senses the channel busy, and it has to wait for $N+A$ time slots

$$P\{(j,k,N+A)|(j,k,0)\} = p_b,\ 1 \le k \le W_j,\ 0 \le j \le m+h.$$

5) For states (j,k,d), $j = 0,1,\ldots,m+h$, $k \ge 1$ and $1 \le d$, when one time slot has elapsed during the frozen period, the remaining frozen time is reduced by one

$$P\{(j,k,d-1)|(j,k,d)\} = 1, \quad 1 \le k \le W_j,\ 0 \le j \le m+h,\ A+1 \le d \le N+A.$$

During the post-AIFS period after the frozen period, if the channel is determined to be idle, the remaining frozen time decreases by one. However, if at the end of the second last slot of the AIFS the channel is still idle, the counter decreases by one as emphasized before

$$\begin{cases} P\{(j,k,d-1)|(j,k,d)\} = 1-p_b, \\ \qquad 1 \le k \le W_j, 0 \le j \le m+h, 2 \le d \le A \\ P\{(j,k-1,0)|(j,k,1)\} = 1-p_b, \\ \qquad 1 \le k \le W_j, 0 \le j \le m+h. \end{cases}$$

During such post-AIFS period, if the channel is determined to be busy, the counter is frozen, and the remaining frozen time is reset to $N+A$

$$P\{(j,k,N+A)|(j,k,d)\} = p_b, \quad 1 \le k \le W_j,\ 0 \le j \le m+h,\ 1 \le d \le A.$$

6) For states $(-1,0,d)$, $d = 0,1,\ldots,N+A$, when a new packet is ready for transmission, the AC senses the channel for an AIFS period. If the channel remains idle at the end of the AIFS period, the backoff is invoked. If at any time the channel is no longer idle, the AC defers access attempt without invoking the backoff procedure

$$\begin{cases} P\{(-1,0,d-1)|(-1,0,d)\} = 1-p_b, & 1 \le d \le A \\ P\{(0,k,0)|(-1,0,0)\} = \frac{1-p_b}{W_0+1}, & 0 \le k \le W_0 \\ P\{(-1,0,N+A)|(-1,0,d)\} = p_b, & 0 \le d \le A \\ P\{(-1,0,d-1)|(-1,0,d)\} = 1, & A+1 \le d \le N+A \end{cases}.$$

All of these transition probabilities are illustrated in the transition diagrams of Figs. 4 and 5.

C. System Equations

Let $b_{j,k,d}$ be the steady probability of state (j,k,d). Similar to [16] and [17], we have

$$b_{j,0,0} = p_i^j b_{0,0,0}, \quad 0 \le j \le m+h \tag{1}$$

and

$$b_{j,k,0} = \frac{W_j+1-k}{W_j+1} b_{j,0,0}, \quad 0 \le j \le m+h,\ 1 \le k \le W_j. \tag{2}$$

For the third dimension, due to the regularity of the Markov chain, all the following relations hold:

$$\begin{cases} b_{j,k,d} = \frac{p_b}{(1-p_b)^A} b_{j,k,0}, \\ \qquad A \le d \le N+A, 1 \le k \le W_j, 0 \le j \le m+h \\ b_{j,k,d} = \frac{p_b}{(1-p_b)^d} b_{j,k,0}, \\ \qquad 1 \le d \le A-1, 1 \le k \le W_j, 0 \le j \le m+h \\ b_{j,0,d} = p_i b_{j,0,0}, \\ \qquad 1 \le d \le \lceil T_c \rceil, 0 \le j \le m+h \end{cases} \tag{3}$$

and

$$\begin{cases} b_{-2,0,d} = \left(1-p_i^{m+h+1}\right) b_{0,0,0}, & 1 \le d \le \lceil T_s \rceil \\ b_{-1,0,d} = \frac{1}{(1-p_b)^{d+1}} b_{0,0,0}, & 0 \le d \le A \\ b_{-1,0,d} = \frac{1-(1-p_b)^{A+1}}{(1-p_b)^{A+1}} b_{0,0,0}, & A+1 \le d \le N+A \end{cases}. \tag{4}$$

By substituting (1) into (2) and (3), all the probabilities $b_{j,k,d}$ can be expressed in terms of p_b, the channel busy probability and p_i, the collision probability of ACi, and $b_{0,0,0}$ which can be derived from the normalization condition as follows:

$$\begin{aligned} 1 &= \sum_{d=1}^{\lceil T_s \rceil} b_{-2,0,d} + \sum_{d=0}^{N+A} b_{-1,0,d} + \sum_{j=0}^{m+h} \sum_{d=0}^{\lceil T_c \rceil} b_{j,0,d} \\ &\quad + \sum_{j=0}^{m+h} \sum_{k=1}^{W_j} \sum_{d=0}^{N+A} b_{j,k,d} \\ &= b_{0,0,0} \left[\frac{1+Np_b}{p_b} \frac{1-(1-p_b)^{A+1}}{(1-p_b)^{A+1}} + \lceil T_s \rceil \left(1-p_i^{m+h+1}\right) \right. \\ &\qquad + (1+\lceil T_c \rceil p_i) \frac{1-p_i^{m+h+1}}{1-p_i} \\ &\qquad \left. + \frac{1+Np_b}{2(1-p_b)^A} \sum_{j=0}^{m+h} W_j p_i^j \right]. \end{aligned}$$

Therefore, $b_{0,0,0}$ is

$$\begin{aligned} b_{0,0,0} = &\left[\frac{1+Np_b}{p_b} \frac{1-(1-p_b)^{A+1}}{(1-p_b)^{A+1}} + \lceil T_s \rceil \left(1-p_i^{m+h+1}\right) \right. \\ &\left. + (1+\lceil T_c \rceil p_i) \frac{1-p_i^{m+h+1}}{1-p_i} + \frac{1+Np_b}{2(1-p_b)^A} \sum_{j=0}^{m+h} W_j p_i^j \right]^{-1}. \end{aligned} \tag{5}$$

Once the values of T_s, T_c, W_j, m, h, N, A, p_i, and p_b are known, all the steady-state probabilities can be obtained using (1)–(5). Indeed, T_s, T_c, W_j, m, h, N, and A are known for a given AC, the key problem is to calculate p_i and p_b. This is different from the derivation of those DCF models [16]–[20]

because the Markov chain model is for one AC in this case, and each station may have multiple simultaneously active ACs. Thus, p_i and p_b depend on other stations as in the original model as well as on other ACs within the same station.

Let τ_i be the probability that an ACi accesses the medium in a randomly chosen time slot. It is the sum of all the steady-state probabilities of states $(j, 0, 0)$, $j = 0, 1, \ldots m + h$, because, whenever an AC's backoff counter is zero, there is a transmission attempt regardless of the backoff stage. Thus

$$\tau_i = \sum_{j=0}^{m+h} b_{j,0,0} = \sum_{j=0}^{m+h} p_i^j b_{0,0,0} = \frac{1 - p_i^{m+h+1}}{1 - p_i} b_{0,0,0}. \quad (6)$$

From the viewpoint of a station, the probability τ that the station accesses the channel is, therefore

$$\tau = 1 - \sum_{i=0}^{3} (1 - \tau_i). \quad (7)$$

For one AC, the channel is occupied if the transmission or the collision is related to this AC. So the probability υ_i that the channel is occupied by the given ACi is

$$\upsilon_i = \sum_{d=1}^{\lceil T_s \rceil} b_{-2,0,d} + \sum_{j=0}^{m+h} \sum_{d=0}^{\lceil T_c \rceil} b_{j,0,d}. \quad (8)$$

Similarly, the probability υ that the channel is occupied by a station is

$$\upsilon = 1 - \sum_{i=0}^{3} (1 - \upsilon_i). \quad (9)$$

Finally, the channel is deemed idle if and only if no station is using it. As a result, p_b, the probability that the channel is busy is given by

$$p_b = 1 - (1 - \upsilon)^M \quad (10)$$

where M is the total number of active stations. Due to both external collision and internal collision, the conditional collision probabilities of ACi is

$$p_i = 1 - (1 - \tau)^{M-1} \prod_{i' > i} (1 - \tau_{i'}) \quad (11)$$

where $i' > i$ means that ACi$'$ has higher priority than ACi.

Equations (6)–(11) form a set of nonlinear equations. It can be solved by means of numerical methods. All the transition probabilities and steady-state probabilities can be obtained.

IV. Performance Analysis

A. Throughput Analysis

The normalized throughput of a given AC is calculated as the ratio of time occupied by the transmitted information to the interval between two consecutive transmissions. According to this definition, the throughout of ACi, S_i is expressed as

$$S_i = \frac{p_{si} E[P]}{E[I] + \sum_{i'=0}^{3} p_{si'} \left(T_s + \mathrm{AIFS[ACi']}\right) + \left(1 - \sum_{i'=0}^{3} p_{si'}\right) T_c} \quad (12)$$

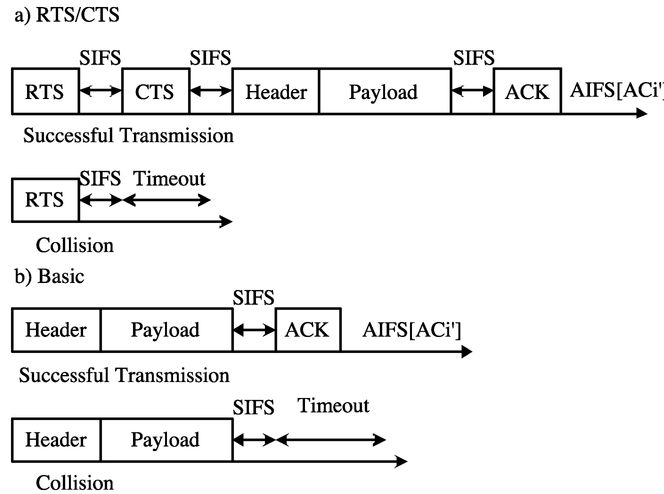


Fig. 6. Successful transmission time and collision time. (a) RTS/CTS access mode. (b) Basic access mode.

where P is payload size, $E[I]$ is the expected value of idle time slots before a transmission, p_{si} and $p_{si'}$ are the conditional successful transmission probabilities for ACi and ACi$'$, respectively, T_s is the average successful transmission time, T_c is the collision time, and AIFS[ACi$'$] is the AIFS period of ACi$'$.

From Fig. 6, T_s and T_c can be written, respectively, as for the RTS/CTS access mode

$$\begin{cases} T_s = \mathrm{RTS} + \mathrm{SIFS} + \mathrm{CTS} + \mathrm{SIFS} + \mathrm{H} + \mathrm{P} \\ \qquad + \mathrm{SIFS} + \mathrm{ACK} + \mathrm{AIFS[ACi']} \\ T_c = \mathrm{RTS} + \mathrm{SIFS} + \mathrm{CTS\_Timeout} \end{cases} \quad (13)$$

and for the basic access mode

$$\begin{cases} T_s = H + P + \mathrm{SIFS} + \mathrm{ACK} + \mathrm{AIFS[ACi']} \\ T_c = H + P + \mathrm{SIFS} + \mathrm{ACK\_Timeout} \end{cases} \quad (14)$$

where H represents the physical and MAC layer headers. During a successful transmission, other ACs' counters are frozen according to T_s.

An ACi's frame can be transmitted successfully only when no other higher priority AC in the same station and no other station of the remaining $M - 1$ transmits. Therefore, the conditional successful transmission probability p_{si}, is given by

$$p_{si} = \frac{M p_{ti} (1 - \upsilon)^{M-1} \prod_{i' > i} (1 - \upsilon_{i'})}{1 - (1 - \upsilon)^M} \quad (15)$$

where p_{ti}, the successful transmission probability of ACi is given by

$$p_{ti} = \sum_{d=1}^{\lceil T_s \rceil} b_{-2,0,d}. \quad (16)$$

Finally, the mean idle period can be easily obtained as

$$E[I] = \frac{1}{p_b} - 1. \quad (17)$$

By substituting (13)–(17) into (12), the normalized throughput for ACi can be readily obtained.

B. Delay Analysis

We investigate the mean access delay (i.e., the average time between the first transmission attempt of a packet until it is successfully transmitted). We propose a recursive method to calculate this delay.

Let $D_{j,k,d}$ be the time delay from current state (j,k,d) until the packet is transmitted successfully. Suppose $D_{j,k-1,0}$ is known, the relationships of the delay between states $(j,k-1,0)$ and (j,k,d), $d=0,1,\ldots,N+A$, are

$$\begin{cases} D_{j,k,d}=(1-p_b)D_{j,k-1,0} \\ \qquad +p_bD_{j,k,N+A}+1, \quad d=0,1 \\ D_{j,k,d}=(1-p_b)D_{j,k,0} \\ \qquad +p_bD_{j,k,N+A}+1, \quad 2\le d\le A \\ D_{j,k,d}=D_{j,k,d-1}+1, \qquad A+1\le d\le N+A. \end{cases} \tag{18}$$

Equation (18) constructs a set of linear equations which can be solved for all $D_{j,k,d}$, $d=0,1,\ldots,N+A$ once $D_{j,k-1,0}$ is known. Using the same method, $D_{j,k+1,d}$, $d=0,1,\ldots,N+A$, can also be obtained. Therefore, the delay for each state in backoff stage j can be attained as long as $D_{j,0,0}$ is known.

For states $(j,0,0)$, $0\le j\le m+h-1$, the transmission is either a successful transmission or a collision. Thus, the delay $D_{j,0,0}$ is expressed as

$$D_{j,0,0}=p_i\left(D_{j,0,\lceil T_c\rceil}+1\right)+(1-p_i), \quad 0\le j\le m+h-1 \tag{19}$$

where $D_{j,0,\lceil T_c\rceil}$ is obtained from the following relations. For states $(j,0,d)$, $d=1,\ldots,\lceil T_c\rceil$, we have

$$\begin{cases} D_{j,0,d}=D_{j,0,d-1}+1, \qquad 2\le d\le\lceil T_c\rceil \\ D_{j,0,1}=\sum_{k=0}^{W_{j+1}}\frac{D_{j+1,k,0}}{W_{j+1}+1}+1, \end{cases}. \tag{20}$$

The delays of the initial states $(-1,0,d)$, $d=0,1,\ldots,N+A$, are given by

$$\begin{cases} D_{-1,0,0}=(1-p_b)\sum_{k=0}^{W_0}\frac{D_{0,k,0}}{W_0+1}+1 \\ D_{-1,0,d}=(1-p_b)(D_{-1,0,d-1}+1) \\ \qquad +p_b(D_{-1,0,N+A}+1), \quad 1\le d\le A, \\ D_{-1,0,d}=D_{-1,0,d-1}+1, \qquad A+1\le d\le N+A \end{cases}. \tag{21}$$

For the whole Markov chain, once $D_{m+h,0,0}$ is known, the evaluation of the delays of all the states is carried out in a bottom-to-top and left-to-right manner. As a matter of fact, for state $(m+h,0,0)$, if the packet cannot be sent out at this time, it will be discarded, so the access delay is one time slot and, thus

$$D_{m+h,0,0}=1.$$

Therefore, all the $D_{j,k,d}$ can be obtained, and consequently, the mean access delay for this system can be expressed as

$$D=\sum_{d=0}^{N+A}b_{-1,0,d}D_{-1,0,d}+\sum_{j=0}^{m+h}\sum_{d=0}^{\lceil T_c\rceil}b_{j,0,d}D_{j,0,d} + \sum_{j=0}^{m+h}\sum_{k=1}^{W_j}\sum_{d=0}^{N+A}b_{j,k,d}D_{j,k,d}. \tag{22}$$

TABLE I
CALCULATION AND SIMULATION PARAMETERS

Payload Size	1000 bytes
Phy Header(including preamble)	192bits
Mac Header(including CRC bits)	272bits
RTS Frame	Phy Header+160bits
CTS Frame	Phy Header+112bits
ACK Frame	Phy Header+112bits
CTS_Timeout	DIFS+CTS
ACK_Timeout	DIFS+ACK
Data Rate	11 Mbps
Time Slot	$20\mu s$
SIFS	1 Time Slot
AIFS[AC3]	3 Time Slots
AIFS[AC1]	4 Time Slots
CW[AC3]	{15, 31, 63, 127}
CW[AC1]	{31, 63, 127, 255}

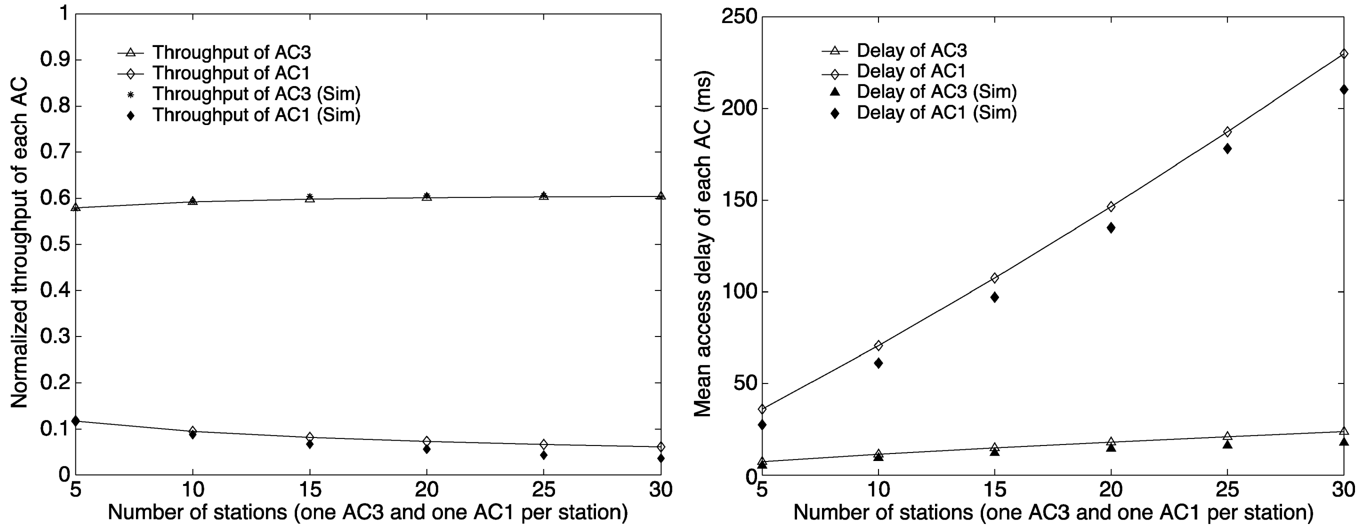
V. NUMERICAL AND SIMULATION RESULTS

In this section, we first compare the numerical results of the model with simulation results using NS2 [23]. Then, we investigate how the performance of the EDCA is affected by the CW and the AIFS values of different ACs. RTS/CTS mechanism is employed. For simplicity and without loss of generality, we assume that there are two active ACs in each station, one is AC3 with a higher priority, and the other is AC1 with a lower priority. The values of the parameters used are listed in Table I.

A. Model Validation

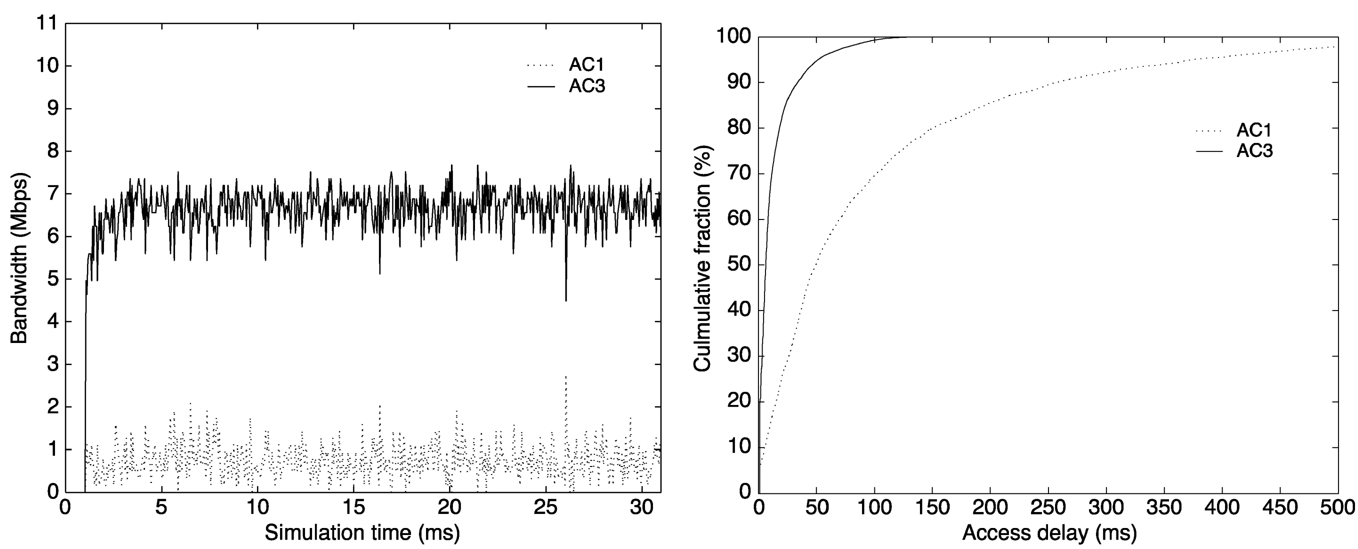
Fig. 7 shows the simulation and numerical results of the normalized throughput and mean access delay performance of AC3 and AC1 against the number of stations in the network. Fig. 8 shows the simulation results for a particular case in which the number of stations equal to 15, and each station has one AC3 and one AC1. Fig. 8(a) shows the bandwidth occupied by AC3 and AC1. The mean value of this bandwidth is just the normalized throughput multiplied by the data rate, which is 11 Mb/s in this case. Fig. 8(b) shows the access delay distribution of AC3 and AC1. In regard to both the throughput and delay performance, it can be seen that the model yields results that match well with simulation results.

It can also be noted that EDCA mechanism provides an effective way of differentiation. The higher priority traffic AC3 always achieves much higher bandwidth than the lower priority traffic AC1, and the former always suffers a smaller access delay than the latter. As the number of stations in the network increases, the throughput of AC3 remains relatively constant, while that of AC1 decreases by about half. This occurs because the more stations there are, the more AC3 traffic contends for the medium. This causes AC1 to lose more chances of transmission. This phenomenon is also revealed by the results of the access delay performance. The more stations there are in the network, the more collisions there are. This leads to a longer backoff time for each AC and, therefore, to an increase in the access delay for both AC3 and AC1, but AC1 increases much faster than AC3.



(a) (b)

Fig. 7. Numerical and simulation results for normalized throughput and mean access delay. (a) Normalized throughput. (b) Mean access delay.



(a) (b)

Fig. 8. Simulation results for achieved bandwidth and access delay distribution. (a) Bandwidth. (b) Access delay distribution.

B. Effects of the CW

In order to investigate the effects of the CW on the performance of the system, two sets of CWs are used for AC3: $\mathrm{CW[AC3]} = \{7, 15, 31, 63\}$ and $\mathrm{CW[AC3]} = \{31, 63\, 127\, 255\}$.

Fig. 9 shows the normalized throughput and mean access delay performance of AC3 and AC1 against the number of stations with different CWs for AC3. When the CW of AC3 becomes smaller, AC3 gains more opportunities for transmission and achieves a smaller access delay. It can be noted that when the CW of AC3 is {31, 63, 127, 255}, although the same as that of AC1, the performances achieved by the two ACs are different. This is because AC3 has a smaller AFIS than AC1, which forces AC1 to sense the channel for a longer time than AC3. This helps AC3 greatly after a successful transmission or after it finishes deferring. When the CW of AC3 changes to {7, 15, 31, 63}, AC3 obtains more chances to transmit and, at the same time, to "push" AC1 back. Thus, the throughput of AC3 increases and the access delay decreases, while the throughput and access delay of AC1 follow the opposite trend.

An interesting observation is that when the CW of AC3 is {7, 15, 31, 63}, the throughput of AC3 is much higher than that of AC1. However, as the number of stations increases, AC3's throughput decreases slightly. When the CW of AC3 is {15, 31, 63, 127}, the throughput is almost constant, but when the CW is {31, 63, 127, 255}, the throughput of AC3 increases. This indicates that, as the number of higher priority ACs increases, the differentiation effect of the CW size on the throughput becomes less and less significantly because most collisions occur among AC3 flows.

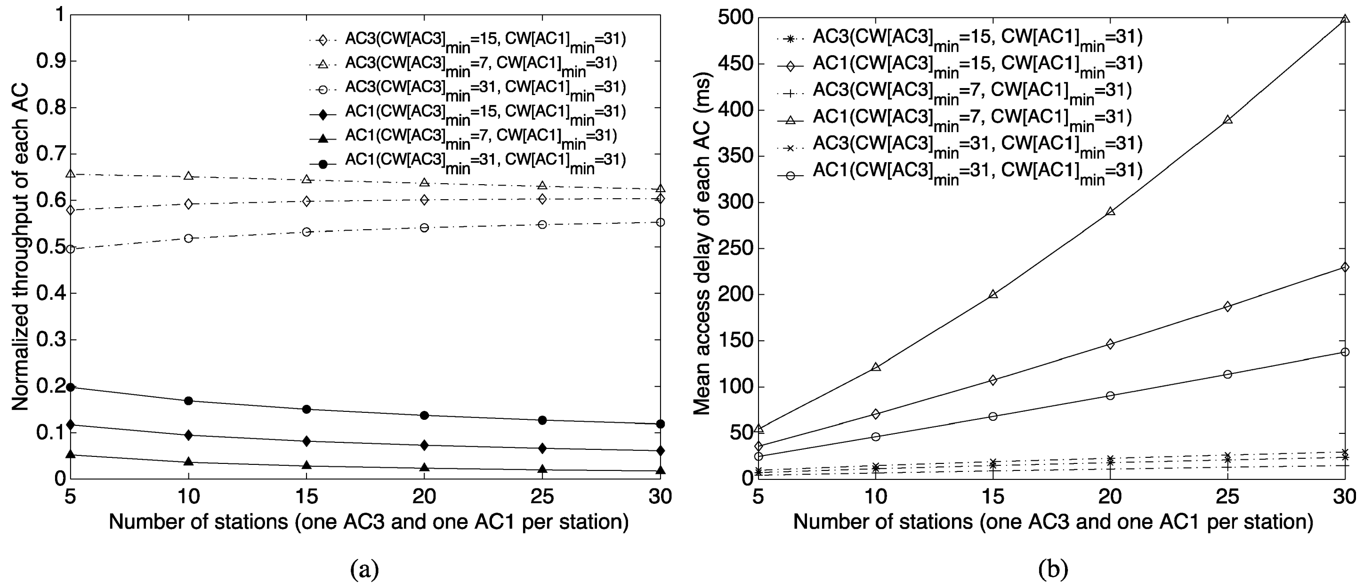


Fig. 9. Service differentiation effectiveness and effects of different CWs. (a) Normalized throughput. (b) Mean access delay.

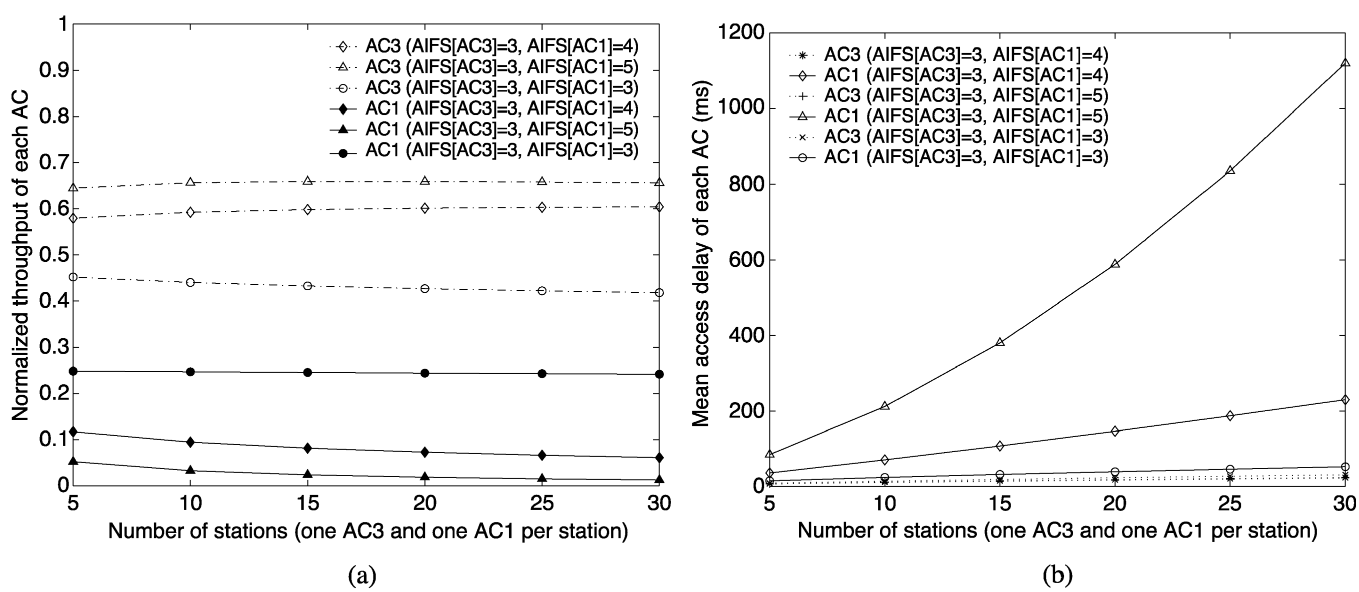


Fig. 10. Service differentiation effectiveness and effects of different AIFSs. (a) Normalized throughput. (b) Mean access delay.

C. Effects of AIFS

Different AIFSs for AC1 $\mathrm{AIFS[AC1]} = 3$, $\mathrm{AIFS[AC1]} = 4$ and $\mathrm{AIFS[AC1]} = 5$ are employed to study the effects of AIFS.

Fig. 10 shows the normalized throughput and mean access delay performance of AC3 and AC1 against the number of stations, with different AIFSs for AC1. It can be noted that the AIFS is also very effective to provide service differentiation. When the AIFS for AC3 and AC1 are equal, $\mathrm{AIFS[AC3]} = \mathrm{AIFS[AC1]} = 3$, there are still some gaps between the throughput and access delay performance due to different CWs of AC3 and AC1. When the AIFS of AC1 increases to 4 and 5, the throughput of AC3 and AC1 increases and decreases, respectively, and the access delay becomes smaller for AC3 (respectively, larger for AC1).

A surprising result is when the AIFS of AC1 changes from 4 to 5, the access delay of AC3 does not improve very much. This is because it is already very small and there is little room for improvement. The access delay of AC1, however, increases dramatically. This suggests that although the differentiation provided by the AIFS is very effective, it can have a dramatic negative effect when the network is heavily loaded, in which it can lead the lower priority traffic to starvation.

D. Heterogeneous Situation

All the above results and discussions have been obtained under the situation where each station always has one AC3 and one AC1 active. In this section, we investigate the performance when each station has only one single AC active, either AC3 or AC1. In this case, there is no internal collision. Therefore, some minor modifications are needed for the derivation.

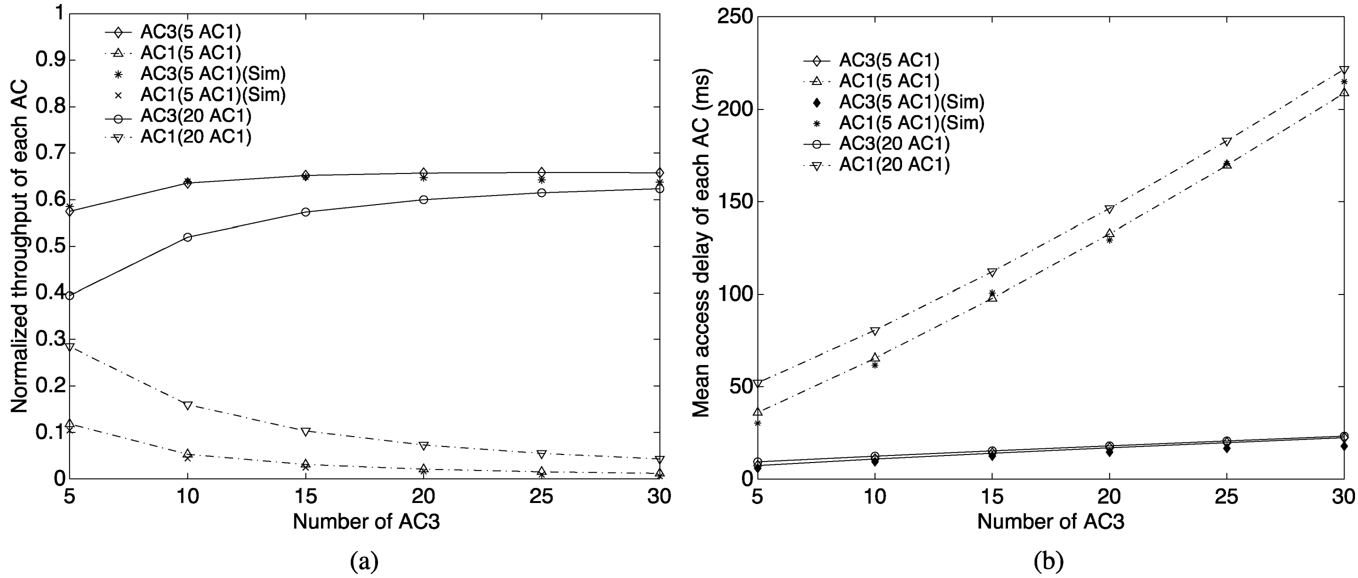


Fig. 11. Performance of heterogeneous situation with fixed number of AC1. (a) Normalized throughput. (b) Mean access delay.

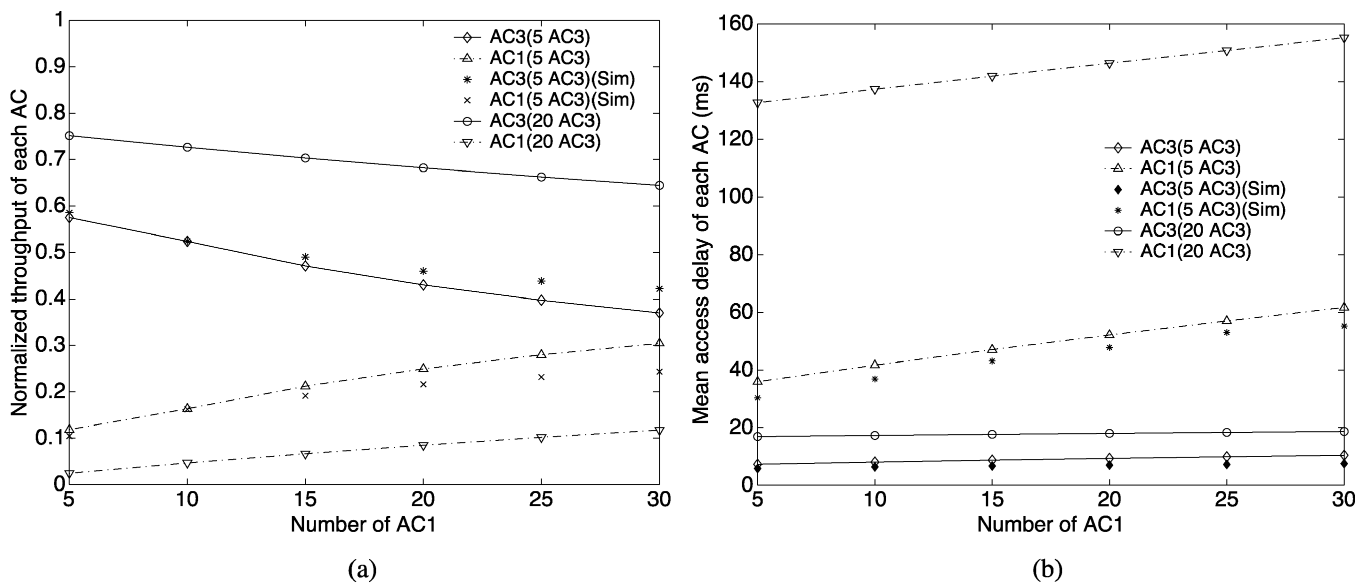


Fig. 12. Performance of heterogeneous situation with fixed number of AC3. (a) Normalized throughput. (b) Mean access delay.

Assuming there are M_3 stations with AC3 and M_1 stations with AC1, the probability of channel busy is given by

$$p_b = 1 - (1-\upsilon_3)^{M_3}(1-\upsilon_1)^{M_1}$$

where υ_3 and υ_1 are still calculated using (8). The conditional collision probabilities of AC3 and AC1 are

$$\begin{cases} p_3 = 1 - (1-\tau_3)^{M_3-1}(1-\tau_1)^{M_1} \\ p_1 = 1 - (1-\tau_3)^{M_3}(1-\tau_1)^{M_1-1} \end{cases}$$

where τ_3 and τ_1 are computed from (6).

The conditional successful transmission probabilities of AC3 and AC1, p_{s3} and p_{s1} are calculated as

$$\begin{cases} p_{s3} = \frac{M_3 p_{t3}(1-\upsilon_3)^{M_3-1}(1-\upsilon_1)^{M_1}}{1-(1-\upsilon_3)^{M_3}(1-\upsilon_1)^{M_1}} \\ p_{s1} = \frac{M_1 p_{t1}(1-\upsilon_3)^{M_3}(1-\upsilon_1)^{M_1-1}}{1-(1-\upsilon_3)^{M_3}(1-\upsilon_1)^{M_1}} \end{cases}$$

where p_{t3} and p_{t1} are obtained using (16). All the other derivations and results of the throughput and delay are the same as before with substitutions of the corresponding probabilities.

Fig. 11 shows the normalized throughput and mean access delay performance with a fixed M_1 as 5 and 20, respectively, and M_3 varied from 5 to 30. For comparison, Fig. 12 shows the results obtained by setting M_3 as 5 and 20 and allowing M_1 changes from 5 to 30.

It can be seen that when the number of AC1 is fixed, the number of AC3, M_3, affects AC1's performance so greatly that both the throughput and delay degrade significantly. The delay of AC3 also increases, but the throughput only improves when M_3 increases from 5 to 15. Then, it remains at a constant level, especially when the number of AC1 is small. However, if the number of AC3 is fixed and the number of AC1 is changed as shown in Fig. 12, the delay of AC3 changes marginally, and the delay of AC1 does not increase greatly. The normalized throughput is greatly enhanced for AC1 and reduced for AC3, especially when the fraction of AC3 is small.

From the above results, it can be noted that the number of higher priority ACs, in our scenario AC3, should be limited in order to guarantee an acceptable throughput and delay performance for both AC3 and AC1. This functionality can be realized via some call admission control (CAC) schemes, which will be the focus of our future work.

VI. Conclusion

In this paper, we have presented an analytical model to analyze the performance of EDCA, the contention-based channel access mechanism in the forthcoming IEEE 802.11e protocol. All the important new features of the EDCA, viz., virtual collision, different AIFS, and CW have been taken into account. We also considered the difference of the countdown procedure between the EDCA and the legacy DCF, as well as the retransmission limit.

Based on the proposed model, we have studied the throughput performance for multiclass priority traffic and have proposed a recursive method to calculate the mean access delay. The model and results are validated via simulations. The effects of the CW and AIFS on the service differentiation ability of the protocol have been investigated. We also suggest that the number of ACs, or in other words, the traffic load, should be limited in order to provide a relatively satisfactory service level for both high-priority and low-priority ACs.

The model and analysis provide an in-depth understanding and insights into the EDCA mechanism. They also provide helpful and powerful tools for further study, such as parameterization for some types of traffic and development of call admission control schemes for further QoS improvement for WLANs.

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