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Performance Evaluation for Next Generation Differentiated Services in Wireless Local Area Networks

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With the provisioning of high-speed wireless LAN (WLAN) environments, multimedia services (*e.g.*, VoIP and video-conference) with different QoS requirements will be available in next generation WLANs. Multimedia services could be categorized into multiple traffic classes and different priorities will be applied to access the wireless medium. The IEEE 802.11 working group has been developing a new generation distributed access protocol, called enhanced distributed channel access (EDCA), to support service differentiation in the 802.11 MAC layer. Service differentiation is achieved by assigning different values of EDCA access parameters (*i.e.*, minimum contention window, maximum contention window, and arbitration interframe space) to different traffic classes. To investigate the system performance under various network conditions, it is helpful to have a theoretical model for EDCA. In this paper, we introduce an analytical model for EDCA so that the saturation bandwidth can be estimated by closed-form formulas for each traffic class. We use *ns*-2 simulator to validate the analytical model. Some numerical results are provided to evaluate the performance of EDCA. The numerical results demonstrate the corresponding effects for tuning different EDCA access parameters.

Keywords: analytical model, IEEE 802.11, medium access control, performance evaluation, wireless local area networks

1. INTRODUCTION

Recent developments in the IEEE 802.11 standardizations [3] have been able to offer broadband multimedia services. Hence, multiple traffic classes (*e.g.*, VoIP and video-conference) with different QoS requirements such as delay-toleration and required bandwidth will be available in new generation WLANs. However, in the current access mechanism of IEEE 802.11, all of the mobile stations apply the same priority to access the wireless medium. To satisfy multiple traffic classes with different QoS requirements, it is desired to provide service differentiation in the IEEE 802.11 standard [16].

To obtain service differentiation in a wireless environment requires the MAC protocol to offer different access priorities among different traffic classes. Recently, the IEEE

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802.11 working group has been developing a new standard, called IEEE 802.11e [6], to support service differentiation in the MAC layer. The forthcoming IEEE 802.11e standard introduces a new medium access mechanism, called hybrid coordination function (HCF), which coexists with original IEEE 802.11 MAC for backward compatibility. HCF consists OF distributed and centralized access methods. The distributed access method, called EDCA, is an extension of the existing distributed coordination function (DCF) to support service differentiation. The centralized access method is an enhancement of the existing point coordination function (PCF) to support more efficient scheduling or polling schemes. The adoption of the centralized access method has been limited due to higher overhead, cost, complexity and issues in scalability, practicality and flexibility [22]. Hence we only focus our attention on EDCA in the paper.

There were a number of theoretical results that explore the performance of DCF. In [11], Cali, Conti and Gregori optimized the throughput by dynamically tuning the values of DCF parameters. In [9], Bianchi suggested a theoretical model based on the two-dimensional Markov chain to estimate the saturation throughput. Later, Ziouva and Antonakopoulos [32] extended Bianchi's model by taking account of busy medium conditions in the backoff algorithm. Ada and Castellucia [7] first suggested three service differentiation mechanisms for DCF. Veres, Capmbell, Barry and Sun [26] also provided a service differentiation mechanism and they estimated the throughput and delay for admission control by virtual MAC and virtual source protocols.

EDCA provides service differentiation by assigning different values of access parameters among different traffic classes. The design concepts of EDCA are similar to [7, 26]. The effectiveness of service differentiation for EDCA has been verified via simulation [12, 14, 15, 20, 21, 25] and theoretical analysis [10, 13, 18, 19, 23, 27-31]. In [10, 13], they investigated IFS-based priority of EDCA in more detail but not explained all features introduced by EDCA. In [27-31], they calculated the saturation throughput of each traffic class by referring to Bianchi's two-dimensional Markov chain model, which remains a two-dimensional Markov chain model or extends to a three-dimensional Markov chain model. The two-dimensional or three-dimensional Markov chains can be solved by an iterative algorithm. However, an iterative algorithm is quite complicated and can not be executed in a real time fashion. In this paper, a different analytical model is proposed. Instead, a closed-form formula is derived for calculating the saturation bandwidth of each traffic class. Since the calculation of the formula is efficient, it can serve as functions for real-time decision in MAC layer or network layer, *e.g.* admission control [8, 19]. The model proposed in [23] considers multiple flows in a station, which is more realistic by comparing with our proposed model. However, it also adopted a two-dimensional Markov chain, which could not be served for real time usage. Many ideas of the proposed analytical model are motivated from [9, 11] but we generalize the model of [9, 11] to support differentiated services.

The rest of this paper is organized as follows. Section 2 reviews the DCF and EDCA protocols. Section 3 suggests an analytical model under which the saturation bandwidth of each traffic class is estimated. Section 4 validates the analytical model by simulation and evaluates the performance of EDCA. Section 5 concludes this paper with some remarks and further research topics.

2. DCF AND EDCA

In this section, we first describe a basic access method, *i.e.*, DCF, of the IEEE 802.11 MAC protocol, and then describe its enhanced version, EDCA in order to support service differentiation.

2.1 DCF

DCF operates based on carrier sense multiple access with collision avoidance (CSMA/CA). A mobile station that intends to transmit a packet first senses the channel. If the channel is idle for a time period of DCF interframe space (DIFS), it can immediately start transmission. Otherwise, it generates a backoff counter. The counter starts decrement if the channel is sensed idle for a time period of DIFS. Then the counter continues to decrease until the channel is busy or the counter counts down to zero. If the channel is busy, the decrement will pause and resume after another idle time period of DIFS. When the counter counts down to zero, the mobile station starts transmission.

The backoff counter is randomly assigned a value from the range [0, CW − 1], where CW is the contention window. Initially, let CW = CW_{min}, the minimum contention window. When the transmission (or retransmission) fails, the value of CW is doubled until it reaches the maximum $CW_{max} = 2^m CW_{min}$, where m is called the maximum backoff stage.

DCF employs two access mechanisms for packet transmission. One is two-way handshaking and the other is four-way handshaking. For the former, an ACK (acknowledgement) message is used to indicate that the transmitted packet has been correctly received by the destination station. For the later, an RTS (request-to-send) message is first sent by the source station. When the destination station receives the RTS, it replies a CTS (clear-to-send) message. After receiving the CTS message, the source station is allowed to transmit a packet. Finally, the destination station informs the source station of a successful transmission by replying an ACK message.

2.2 EDCA

EDCA, which is an enhanced version of DCF, can provide a distributed access mechanism to support service differentiation in IEEE 802.11. EDCA introduces the concept of access categories (ACs). Traffic classes with different ACs utilize distinct values of CW_{min}, CW_{max}, and arbitration interframe spacing number (AIFSN) to contend the channel. There are four ACs specified in IEEE 802.11e as shown in Table 1, where the 802.11b physical layer [4] is used.

Table 1. Four ACs specified in IEEE 802.11e draft 10.0.

	AC_0	AC_1	AC_2	AC_3
Values of AIFSN	7	3	2	2
Values of CW_{min}	32	32	16	8
Values of CW_{max}	1024	1024	32	16

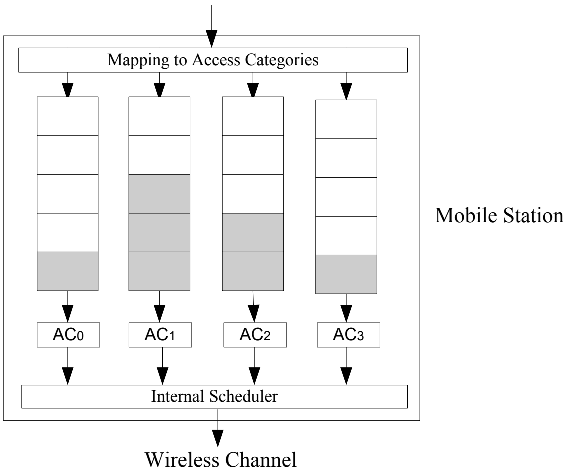


Fig. 1. Four transmission queues in a mobile station.

There are four transmission queues in a mobile station and each is associated with a specific AC, as illustrated in Fig. 1. These queues contend the channel independently and they start their backoff procedures which depend on their associated ACs. If two or more backoff counters reach zero simultaneously, an internal scheduler is responsible for arbitration.

EDCA requires that a mobile station has to wait a time period of AIFS before transmitting a packet or generating a backoff counter. Let T_{AIFS} and T_{SIFS} denote the lengths of AIFS and short IFS (SIFS), respectively. T_{AIFS} is computed as follows: $T_{AIFS} = T_{SIFS} + \text{AIFSN} \times \delta$, where AIFSN ≥ 1 and δ is the length of a time slot. A traffic class with smaller AIFSN has smaller T_{AIFS} and hence has a higher probability of seizing the channel.

3. THE ANALYTICAL MODEL

The environment we consider is a single wireless cell coordinated with an AP. Each mobile station that intends to transmit a packet has to forward its packet to the AP first, even if it is destined for a mobile station located in the same cell. The communication channel is error-free and of no obstacle. Besides, there is no hidden terminal in the system.

Suppose that there are r traffic classes with different QoS requirements in the system, where $r \geq 1$. That is, there are r queues inside a mobile station for which each queue is used for buffering packets of traffic class k. Without loss of generality, we assume that traffic class i has higher priority than traffic class j, where $0 \leq i < j \leq r - 1$. The internal collision resolution mechanism in each station can ensure the transmission of higher-priority traffic, even if there are multiple internal collisions inside the station.

We refer to a packet that belongs to traffic class k as *class-k packet* and a queue that generates class-k packets as *class-k queue*. Each class-k queue is associated with a specific access category, denoted by AC_k, for contending the channel. The parameters CW_{min}, AIFSN, and m (maximum backoff stage) of AC_k are denoted by $CW_{k,\min}$, $AIFSN_k$, and m_k respectively.

Suppose that each class-k packet has constant length L_k and the channel bit rate is M. Hence it takes L_k/M seconds for a class-k queue to transmit a packet. We consider the saturation condition [9], *i.e.*, each queue inside a station always has a packet ready to transmit. The propagation delay for all packets is assumed a constant π.

A discrete and integral time scale is adopted: $[t, t + 1)$ represents a logical time unit. Each queue decreases its backoff counter or transmits a packet at the beginning of each logical time unit. The length of each logical time unit can be any of the following.

- the length of a time slot (δ)
- the time length required for a successful transmission
- the time length required for a colliding transmission

Suppose that a class-k queue transmits a packet at time t, and let $p_k(t)$ be its collision probability. Like [9], we assume that $p_k(t)$ is constant and independent of time, *i.e.*, $p_k(t) = p_k$ for all integers $t \geq 0$. In other words, p_k is independent of the past transmission history. Also let $S_k(t)$ be the backoff stage of the class-k queue at time t, where $0 \leq S_k(t) \leq m_k$. Since $S_k(t + 1)$ depends only on $S_k(t)$, $\{S_k(t): t \geq 0\}$ is a discrete-time Markov chain and its transition diagram is depicted in Fig. 2. It is easy to compute the steady-state probability distribution, denoted by S_k, as follows.

$$\Pr\{S_k = s\} = \begin{cases} (1-p_k)p_k^s, & \text{if } 0 \leq s \leq m_k - 1; \\ \sum_{j=m_k}^{\infty}(1-p_k)p_k^j, & \text{if } s = m_k; \\ 0, & \text{if } s > m_k. \end{cases} \tag{1}$$

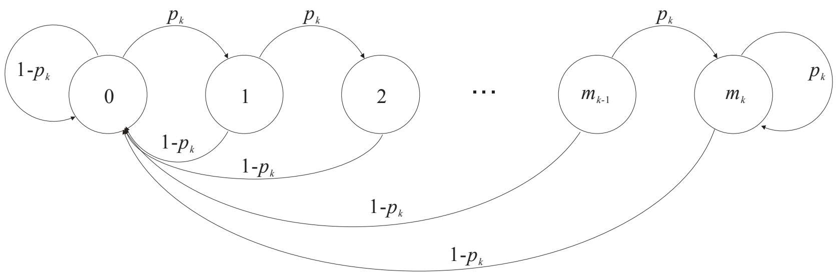


Fig. 2. State transition diagram of $S_k(t)$.

It is noted that the IEEE 802.11 standard has specified a threshold, *i.e.*, backoff retry limit, to avoid colliding under overloading condition. Whenever the number of collisions for a given packet reaches the retry limit, it is simply dropped from the queue. The effect of retry limit is not addressed in Fig. 2. We assume that the retry limit for each traffic class is infinite. In fact, the approximation has insignificant impact on the accuracy of the model since the probability for a packet to have a consecutive collision will be small.

We use B_k to denote the backoff counter that the class-k queue will be assigned, where $0 \le B_k \le 2^{m_k}\mathrm{CW}_{k,\min} - 1$. The distribution of B_k conditioning on backoff stage s is uniform, *i.e.*,

$$\Pr\{B_k = i \mid S_k = s\} = \frac{1}{2^s \mathrm{CW}_{k,\min}}, \text{ for } i = 0,\ 1,\ 2,\ \ldots, 2^s \mathrm{CW}_{k,\min} - 1. \tag{2}$$

Consequently, the average backoff counter of the class-k queue in backoff stage s is computed as

$$E[B_k \mid S_k = s] = \frac{2^s \mathrm{CW}_{k,\min} - 1}{2}, \tag{3}$$

and the average backoff counter of the class-k queue, denoted by $E[B_k]$, is computed as

$$\begin{aligned}
E[B_k] &= \sum_{s=0}^{m_k} E[B_k \mid S_k = s]\Pr\{S_k = s\} \\
&= \sum_{s=0}^{m_k-1} p_k^s (1-p_k)\frac{2^s \mathrm{CW}_{k,\min}-1}{2} + \frac{(2p_k)^{m_k}\mathrm{CW}_{k,\min} - p_k^{m_k}}{2} \\
&= (1-p_k)\frac{\mathrm{CW}_{k,\min}-1}{2} + \ldots + p_k^{m_k-1}(1-p_k)\frac{2^{m_k-1}\mathrm{CW}_{k,\min}-1}{2} + p_k^{m_k}\frac{2^{m_k}\mathrm{CW}_{k,\min}-1}{2} \\
&= \frac{\mathrm{CW}_{k,\min} - 1 + (2p_k\mathrm{CW}_{k,\min} - p_k\mathrm{CW}_{k,\min}) + \ldots + (2^{m_k} p_k^{m_k}\mathrm{CW}_{k,\min} - 2^{m_k-1} p_k^{m_k}\mathrm{CW}_{k,\min})}{2} \\
&= \frac{\mathrm{CW}_{k,\min} - 1 + p_k\mathrm{CW}_{k,\min}\sum_{i=0}^{m_k-1}(2p_k)^i}{2} \\
&= \frac{(1-2p_k)(\mathrm{CW}_{k,\min}-1) + p_k\mathrm{CW}_{k,\min}(1-(2p_k)^{m_k})}{2(1-2p_k)},
\end{aligned}$$

where the last equality holds as $p_k \neq 1/2$. If $p_k = 1/2$, $E[B_k]$ is simply given by omitting the last equality.

The class-k queue has to wait $E[B_k]$ logical time units before it can transmit a packet. In other words, the probability for the class-k queue to transmit a packet at any given time unit is computed as

$$q_k = \frac{1}{E[B_k]+1} = \frac{2(1-2p_k)}{(1-2p_k)(\mathrm{CW}_{k,\min}+1) + p_k\mathrm{CW}_{k,\min}(1-(2p_k)^{m_k})}. \tag{5}$$

The computation of q_k involves p_k, which can be expressed as

$$p_k = p_k^{(I)} + (1 - p_k^{(I)})p^{(E)}, \tag{6}$$

where $p_k^{(I)}$ ($p^{(E)}$) is the probability of internal (external) collision caused by the packet transmission from the class-k queue (the station).

Further, $p_k^{(I)}$ and $p^{(E)}$ can be expressed as follows.

$$p_k^{(I)} = \left(1 - \prod_{0 \le j \le k-1} (1 - q_j)\right), \tag{7}$$

$$p^{(E)} = 1 - (1 - q^{(E)})^{N-1}, \tag{8}$$

where $q^{(E)}$ is the probability of the packet transmission from the station and N is the number of stations in the system.

Let $q_k^{(E)}$ denote the probability of a class-k packet transmitted from the station, *i.e.*,

$$q_k^{(E)} = q_k (1 - p_k^{(I)}). \tag{9}$$

Then, we have

$$q^{(E)} = \sum_{i=0}^{r-1} q_i^{(E)}. \tag{10}$$

With (7)-(10), (6) can be rewritten as

$$p_k = \left(1 - \prod_{0 \le j \le k-1} (1 - q_j)\right) + \prod_{0 \le j \le k-1} (1 - q_j) \left\{1 - \left[1 - \sum_{i=0}^{r-1} q_i \left(1 - \prod_{0 \le i \le k-1} (1 - q_i)\right)^{N-1}\right]\right\}. \tag{11}$$

By using numerical techniques such as Newton's method [2], p_k and q_k can be obtained by solving (5) and (11).

Recall that different traffic classes may have different values of AIFSN. It is natural to involve the value of AIFSN_k in the contention window of the class-k queue. The proposed model will assign the class-k station with a backoff counter from $[\text{AIFSN}_k, 2^s\text{CW}_{k,\min} - 1 + \text{AIFSN}_k]$, instead of $[0, 2^s\text{CW}_{k,\min} - 1]$, in backoff stage s. Consequently, (5) is replaced as

$$\begin{aligned} q_k &= \frac{1}{E[B_k] + \text{AIFSN}_k + 1} \\ &= \frac{2(1 - 2p_k)}{(1 - 2p_k)(\text{CW}_{k,\min} + 1 + \text{AIFSN}_k) + p_k\text{CW}_{k,\min}(1 - (2p_k)^{m_k})}. \end{aligned} \tag{12}$$

In [10] and [13], they show that those models based on the assumption of p_k [9] are not accurate if the differences in AIFSN parameters among different traffic classes are enormous, *e.g.*, the difference between the IFS of two classes is greater than the minimum contention window. However, it is noted that EDCA should be backward compatible with DCF [6]. A mobile station without implementing EDCA has to wait at least a time period of DIFS before it can transmit a packet. Recall that IEEE 802.11 set T_{DIFS}, the length of DIFS, to be $T_{SIFS} + 2 \times \delta$, *i.e.*, it is equivalent to set the value of AIFSN to 2 in EDCA. Since DCF only supports best effort traffic, a mobile station with implementing EDCA will set AIFSN = 1 if it intends to have a higher probability of seizing the channel than best effort traffic. Hence, the backward compatibility restricts the assignment of values of AIFSN among traffic classes. In other words, the difference in AIFSN parameters among different traffic classes should not be too large. Hence, the approximation in (11) and (12) will be reasonably accurate.

When multiple stations contend the channel at the same time, several idle periods and several colliding transmissions will be involved before a successful transmission, as depicted in Fig. 3. We refer to such a cycle as a *transmission cycle*. An idle period is a time interval in which the channel remains idle due to the backoff procedure. A new transmission cycle is initiated whenever a successful transmission ends.

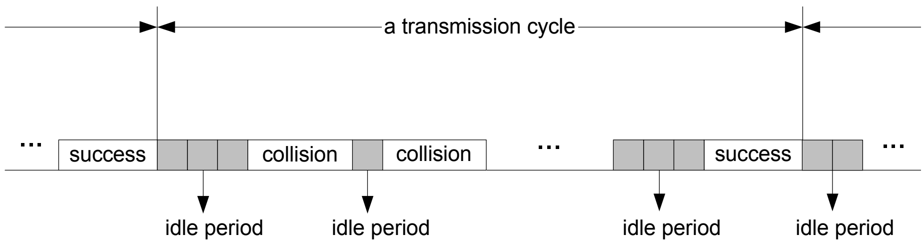


Fig. 3. A transmission cycle.

We assume that the time lengths of all transmission cycles are independently and identically distributed. According to renewal arguments [24], at steady state, the saturation bandwidth for traffic class k, denoted by ρ_k, is given as

$$\rho_k = \frac{P_k}{T_S + T_C + T_I}. \tag{13}$$

where P_k is the average number of bits successfully transmitted for traffic class k during a transmission cycle; T_S, T_C and T_I are the successful transmission period during a transmission cycle, the average time lengths of all idle periods and all colliding transmission periods and, respectively. The computations of P_k, T_S, T_C and T_I are detailed below.

First, P_k can be computed as

$$P_k = \kappa_k L_k, \tag{14}$$

where κ_k is the probability that a class-k packet is successfully transmitted during a transmission cycle and it can be computed as

$$\kappa_k = \Pr\{\text{a class-}k\text{ queue is transmitting} \mid \text{number of transmitting stations} = 1\}$$
$$= \frac{Nq^{(E)}(1-q^{(E)})^{N-1} q_k^{(E)}}{Nq^{(E)}(1-q^{(E)})^{N-1}}. \tag{15}$$

Let T_{PHY}, T_{MAC}, T_{ACK}, T_{RTS} and T_{CTS} be the time lengths required to transmit a physical layer header, a MAC header, an ACK, a RTS and a CTS, respectively. Also let A be

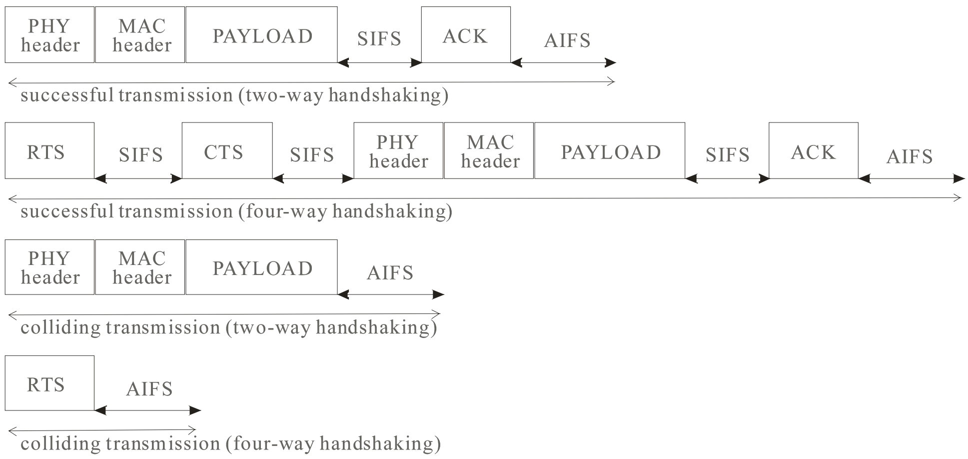


Fig. 4. Successful transmission and colliding transmission under the two-way handshaking and four-way handshaking.

the average value of AIFSN during a transmission cycle, *i.e.*, $A = \sum_{k=0}^{r-1} \kappa_k \mathrm{AIFSN}_k$.

Refer to Fig. 4, and

$$T_S = T_{SIFS} + \delta A + T_{PHY} + T_{MAC} + \sum_{k=0}^{r-1} P_k/M + T_{SIFS} + \pi + T_{PHY} + T_{ACK} + T_{SIFS} + \pi, \quad (16)$$

if the two-way handshaking is adopted, and

$$\begin{aligned} T_S = {} & T_{SIFS} + \delta A + T_{PHY} + T_{RTS} + T_{SIFS} + \pi + T_{PHY} + T_{CTS} + T_{SIFS} + \pi + T_{PHY} + T_{MAC} \\ & + \sum_{k=0}^{r-1} P_k/M + T_{SIFS} + \pi + T_{PHY} + T_{ACK} + T_{SIFS} + \pi, \end{aligned} \quad (17)$$

if the four-way handshaking is adopted.

Let N_c be the number of colliding transmission periods during a transmission cycle. Refer to Fig. 4 again, and

$$T_C = E[N_c](T_{PHY} + T_{MAC} + \sum_{k=0}^{r-1} P_k/M + T_{SIFS} + \delta A + \pi), \quad (18)$$

if the two-way handshaking is adopted, and

$$T_C = E[N_c](T_{PHY} + T_{RTS} + T_{SIFS} + \delta A + \pi), \quad (19)$$

if the four-way handshaking is adopted, where $E[N_c]$ is the average number of colliding transmission periods during a transmission cycle. Clearly, the distribution of N_c is given as

$$\Pr\{N_c = i\} = (1 - p^{(E)})(p^{(E)})^i, \text{ for } i = 0, 1, 2, \ldots, \quad (20)$$

and hence

$$E[N_c] = \frac{p^{(E)}}{1 - p^{(E)}}. \tag{21}$$

We assume that the time lengths of idle periods are independently and identically distributed. Let N_s be the number of time slots contained in an idle period. As shown in Fig. 3, T_I can be computed as

$$T_I = (E[N_c] + 1)\delta E[N_s]. \tag{22}$$

The distribution of N_s can be expressed as

$$\Pr\{N_s = i\} = (1 - (1 - q^{(E)})^N)((1 - q^{(E)})^N)^i, \text{ for } i = 0, 1, 2, \ldots, \tag{23}$$

where $(1 - q^{(E)})^N$ is the probability that no station is transmitted on the channel, *i.e.*, the probability that the channel is idle. Hence,

$$E[N_s] = \sum_{i=0}^{\infty} i(1-(1-q^{(E)})^N)((1-q^{(E)})^N)^i = \frac{(1-q^{(E)})^N}{1-(1-q^{(E)})^N}. \tag{24}$$

4. MODEL VALIDATION AND PERFORMANCE EVALUATION

In this section, the proposed analytical model is first validated via simulation, and then the performance of EDCA is evaluated.

4.1 Model Validation

In order to validate the analytical model, we implemented EDCA by using the *ns*-2 simulator [1]. We also calculated the results of [23] and compare their results with the results obtained by the simulation and the proposed analytical. The values of physical layer parameters were assigned according to the IEEE 802.11a standard [5]. The channel bit rate was assumed to be 24 Mbps. Four traffic classes were assumed, *i.e.*, there were four queues in each station. The payload size for each traffic class was assumed to be 256 bytes. In order to simulate saturation conditions, each traffic class was assumed to have the same inter-arrival time, which was small enough so that each queue always had packets ready for transmission. The values of parameters were summarized in Table 2.

Two scenarios, Scenario I and Scenario II, were simulated. They were assigned with different values of EDCA access parameters, which were summarized in Tables 3 and 4, respectively.

Fig. 5 (Fig. 6) showed the saturation throughputs of Scenario I and Scenario II that were obtained by the proposed analytical model, the simulation and the model of [23] under the two-way handshaking (four-way handshaking). As observed from Figs. 5 and 6, the analytical/simulation results almost coincide with the results of [23] everywhere for all traffic classes.

Table 2. Values of parameters used in the simulation.

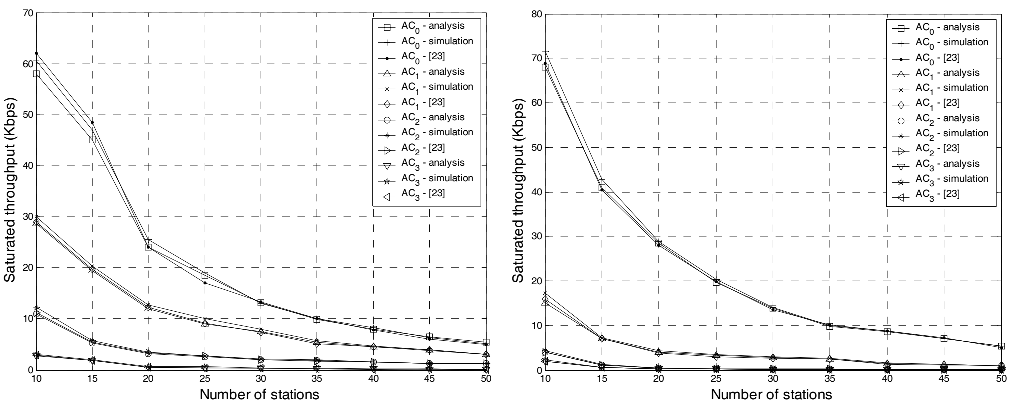
PHY header (including of preamble) T_{PHY}	192μs
MAC header T_{MAC}	28 bytes
Channel bit rate M	24 Mbps
Propagation delay π	1 μs
T_{SIFS}	16 μs
T_{DIFS}	34 μs
T_{RTS}	160 μs + T_{PHY}
T_{CTS}	112 μs + T_{PHY}
T_{ACK}	112 μs + T_{PHY}
Length of a time slot δ	9 μs
Payload size for each traffic class	256 bytes

Table 3. Values of EDCA access parameters for Scenario I.

	AC_0	AC_1	AC_2	AC_3
Values of AIFSN	2	2	3	3
Values of CW_{min}	32	64	64	128
Values of CW_{max}	64	128	256	512

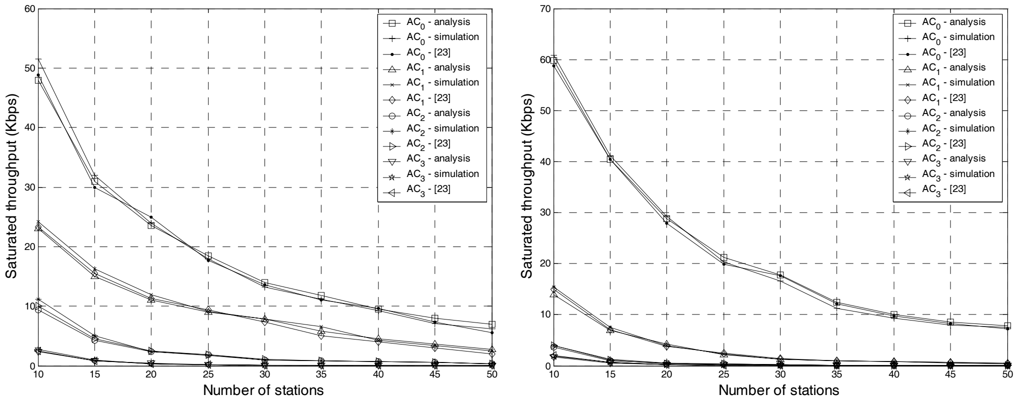
Table 4. Values of EDCA access parameters for Scenario II.

	AC_0	AC_1	AC_2	AC_3
Values of AIFSN	2	2	3	3
Values of CW_{min}	16	32	32	64
Values of CW_{max}	32	64	128	256



(a) Scenario I. (b) Scenario II.

Fig. 5. Model validation under the two-way handshaking.



(a) Scenario I. (b) Scenario II.

Fig. 6. Model validation under the four-way handshaking.

4.2 Performance Evaluation

In this section, the performance of EDCA is evaluated. The performance metrics include the differentiation ratio and the delay. The former showed the ratio of the saturation throughput of each class-i queue to the saturation throughput of the class-0 queue inside a station, where $0 < i \leq 3$. The latter showed the average elapsed time for a packet sent from a sender to a receiver.

The differentiation ratio measures the degree of differentiation between two different traffic classes. The smaller the differentiation ratio is, the greater the degree of differentiation is. The values of the parameters used for the performance evaluation are the same as those assigned in Table 2.

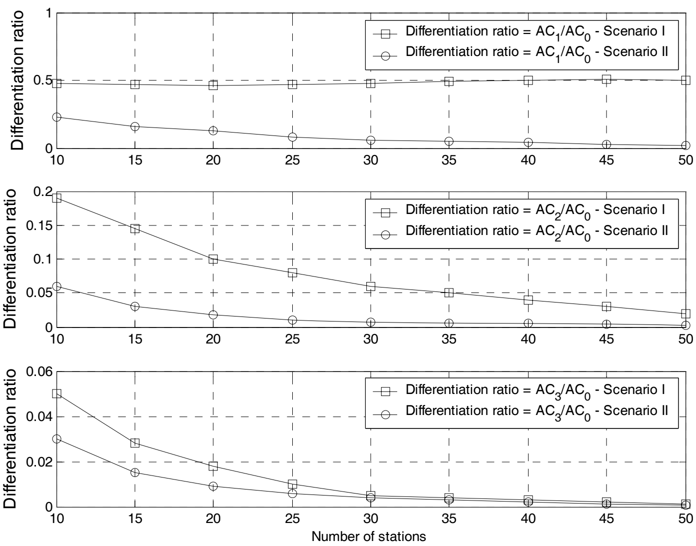


Fig. 7. Differentiation ratios for both scenarios under the two-way handshaking.

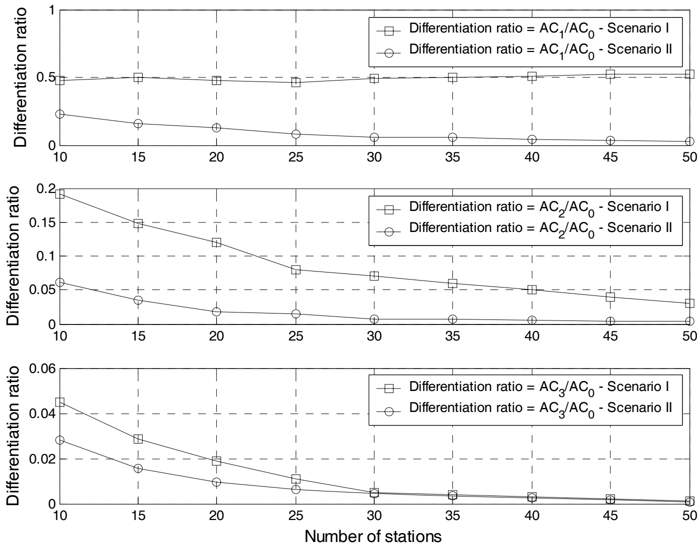
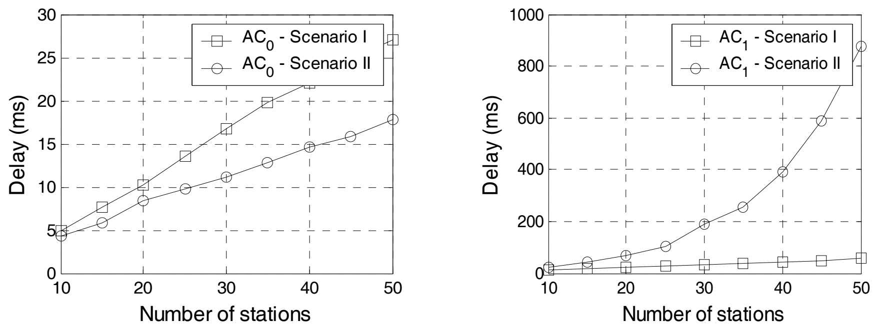


Fig. 8. Differentiation ratios for both scenarios under the four-way handshaking.

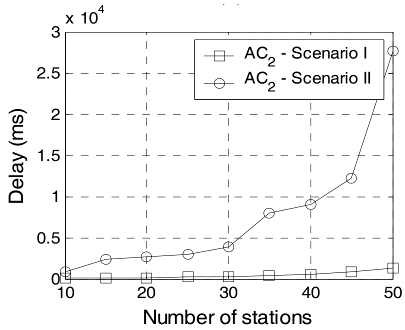
Fig. 7 (Fig. 8) showed the differentiation ratios for both scenarios under the two-way handshaking (four-way handshaking). It was observed that a queue with smaller priority had smaller differentiation ratios for both scenarios. That is, the service differentiation could be realized by EDCA. Moreover, it was also observed that Scenario II had smaller differentiation ratios than Scenario I everywhere, because Scenario II had smaller minimum contention window and smaller maximum contention window for each traffic class than Scenario I. As a consequence, the class-0 queue in Scenario II had a higher probability of capturing the channel than the class-0 queue in Scenario I. In other words, the former had a greater saturation throughput than the latter.

Fig. 9 (Fig. 10) showed the delay of each traffic class for both scenarios under the two-way handshaking (four-way handshaking). It was observed that a queue with higher priority had smaller delays for both scenarios. It was also observed that the class-0 queue in Scenario II had smaller delays than the class-0 queue in Scenario I, while the other

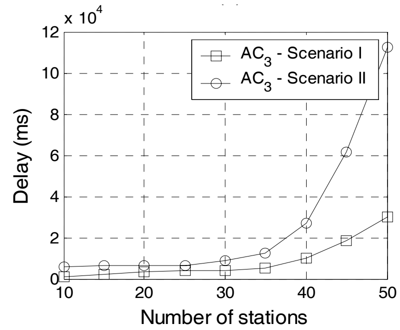


(a) AC_0. (b) AC_1.

Fig. 9. Delays for both scenarios under the two-way handshaking.

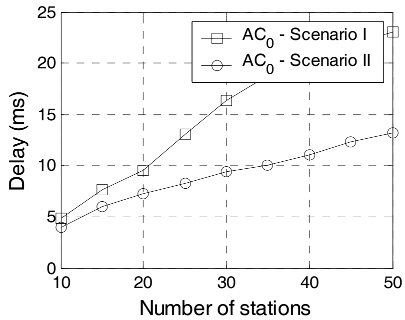


(c) AC_2.

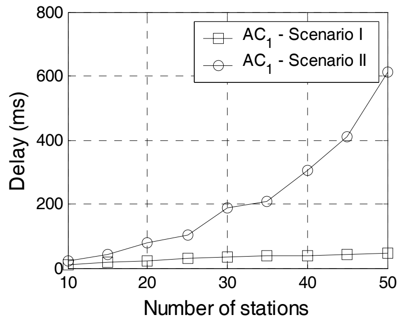


(d) AC_3.

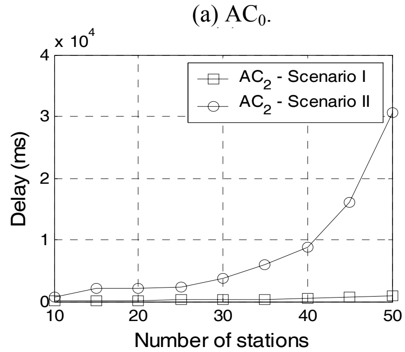
Fig. 9. (Cont'd) Delays for both scenarios under the two-way handshaking.



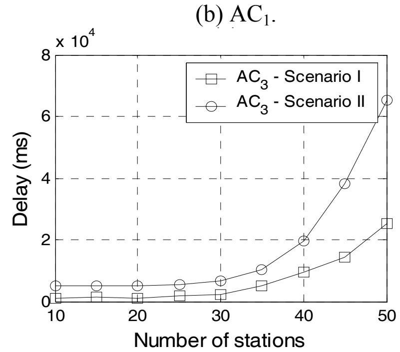
(a) AC_0.



(b) AC_1.



(c) AC_2.



(d) AC_3.

Fig. 10. Delays for both scenarios under the four-way handshaking.

queues in Scenario II had greater delays than the other queues in Scenario I. The reason is the same as that for Figs. 7 and 8, *i.e.*, the class-0 queue in Scenario II had higher probability of capturing the channel than the class-0 queue in Scenario I.

5. DISCUSSION AND CONCLUSION

The future WLANs must accommodate a variety of types of traffic. It is desired to provide service differentiation in MAC protocols for WLANs. Henceforth, emerging interest is in the performance evaluation of EDCA via simulation. It is beneficial to provide an analytical model for evaluating the performance of EDCA from a theoretical viewpoint. However, the theoretical results for EDCA proposed in the recent literature are based on quite complicated multi-dimensional Markov chain models, which can not estimate in a real time fashion. Instead, a closed-form formula was derived in this paper to estimate the saturation bandwidth of each traffic class based on EDCA protocol.

The proposed analytical model could be further used to estimate the capacity of each node in 802.11-based multi-hop wireless networks (*e.g.*, ad hoc networks and wireless mesh networks). Unlike a single-hop environment, each node in a multi-hop environment should maintain the number of contending stations within its interference range. Since the model contained a number of closed-form formulas that could be calculated in a real-time manner, it could be applied for a QoS routing protocol to estimate the remaining bandwidth along a path.

One further research topic is how to dynamically assign different values of EDCA access parameters to different traffic classes under various traffic conditions so that the system performance (*e.g.*, total system throughput) can be optimized. As observed from Figs. 7 and 8, EDCA can support service differentiation by assigning EDCA access parameters with different values for different traffic classes. Moreover, it will induce different saturation throughputs for these traffic classes.

The problem of maximizing the total system throughput can be formulated as a nonlinear programming as follows.

$$\text{Maximize} \ \sum_{k=0}^{r-1} \rho_k$$

subject to

$$\begin{aligned} &C_l \le \mathrm{CW}_{k,\min} \le C_u, && 0 \le k \le r-1; \\ &m_l \le m_k \le m_u, && 0 \le k \le r-1; \\ &A_l \le \mathrm{AIFSN}_k \le A_u, && 0 \le k \le r-1, \end{aligned}$$

where C_l, m_l and A_l (C_u, m_u and A_u) are the lower (upper) bounds on $\mathrm{CW}_{k,\min}$, m_k and AIFSN_k, respectively. The nonlinear programming can be solved by, for example, a gradient-based method [33].

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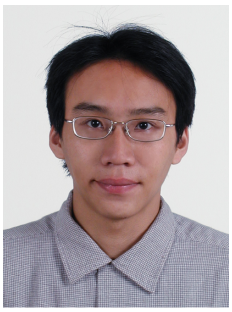

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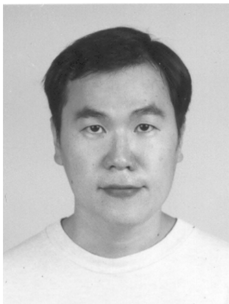

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