

An Analysis of the Coexistence of IEEE 802.11 DCF and IEEE 802.11e EDCA

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Abstract—IEEE 802.11e standard has been published in 2005. In the next few years, we may expect a proliferation of 802.11e capable stations. In the mean time, the legacy 802.11 stations will exist. Therefore, it is of practical significance to study the network performance when 802.11 stations and 802.11e stations coexist. In this paper, a novel Markov chain based analytical model is proposed to investigate the coexistence of DCF and EDCA, which are the fundamental access mechanisms for 802.11 and 802.11e respectively¹. The performance impact of the differences between DCF and EDCA is analyzed, including the contention window (CW) size, the interframe space (IFS), the backoff counter decrement rule, and the transmission timing when the backoff counter reaches zero. Based on the proposed model, the saturated throughput is analyzed. Simulation study is carried out to evaluate the accuracy of the proposed model.

I. INTRODUCTION

IEEE 802.11e standard has been published in 2005. In the next few years, we may expect a proliferation of 802.11e capable stations, which is referred to as QoS stations (QSTA) in the paper. In the mean time, the legacy 802.11 stations, referred to as non-QoS stations (non-QSTA) in the paper, will exist for a rather long time period. Therefore, it is of practical significance to study the network performance when non-QSTAs and QSTAs coexist in the same base station set in which the access point (AP) is capable of supporting IEEE 802.11e standard.

Distributed Coordination Function (DCF) and Enhanced Distribution Channel Access (EDCA) are the fundamental access mechanisms for 802.11 and 802.11e respectively. The major difference between DCF and EDCA is that DCF uses the same backoff parameter set for all stations, while EDCA classifies traffic into four access categories (ACs), i.e., voice, video, best effort, and background, using a set of AC specific parameters, i.e., the contention window (CW) size, the interframe space (IFS)², and the Transmission Opportunity (TXOP) limit. In addition, some other detailed differences between DCF and EDCA exist [1]:

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²A QSTA waits an AIFS (arbitration IFS) after a successful transmission and an EIFS (extended interframe space) after a collision. Here EIFS is the sum of an AIFS and an ACK timeout duration. For simplicity, we use the term " IFS_E " to represent both of them when it is not necessary to specify their difference. Similarly, the term " IFS_D " is used to represent both DIFS (DCF IFS) and DIFS+ACK timeout time duration for non-QSTAs when there is no need to specify their difference.

- 1) Each time a station starts a new backoff procedure or resumes the suspended backoff procedure, it must sense the channel idle for a complete IFS interval from the end of the last busy channel. A QSTA will decrease its backoff counter by one at the beginning of the time slot immediately following the IFS_E , irrespective of the channel status in that time slot. In comparison, a non-QSTA must sense the channel idle in the time slot immediately following the IFS_D too in order to decrease its backoff counter by one at the beginning of the next following time slot. That is, a non-QSTA needs to wait an extra idle time slot. A special case should be noted, when a non-QSTA or a QSTA starts a backoff procedure with an initial backoff counter of zero, both of them can start a transmission immediately after the corresponding IFS. This is the only case that a non-QSTA does not need to wait the extra time slot after the idle IFS_D in its channel contention procedure.
- 2) When a non-QSTA decreases its backoff counter to zero at the beginning of a time slot, it will start a transmission immediately, which is independent of the channel status in this time slot. On the contrary, a QSTA will not transmit immediately when its backoff counter is decreased to zero at the beginning of a time slot. It can only start a transmission at the beginning of the next time slot provided that the channel remains idle in the current time slot. Otherwise the QSTA must wait a complete idle IFS_E after the busy channel and start the transmission after the IFS_E .

Extensive work has been done on analyzing the performance of DCF or EDCA separately. A comprehensive literature review can be found in [2], [3]. Comparatively, the coexistence of DCF and EDCA has not been given sufficient consideration. In [1], [4], some detailed differences between DCF and EDCA are discussed, but an analytical model was not given. In this paper, we will propose a novel Markov chain based analytical model for analyzing the coexistence of DCF and EDCA, where the aforementioned differences will be considered. The rest of the paper is organized as the follows: Section II illustrates our proposed model; saturated throughput is analyzed in Section III; simulation study is shown in Section IV; finally Section V concludes the paper.

II. A MARKOV CHAIN BASED ANALYTICAL MODEL

The following assumptions are used: (i) Traffic at each station is saturated; (ii) Each QSTA carries traffic of one AC only; (iii) The transmission probability of a specific QSTA or non-QSTA in a generic time slot is a constant, which is represented by " τ_E " or " τ_D " respectively. They are unknown variables to be solved; (iv) The number of non-QSTAs (" N_D "), and QSTAs (" N_E ") are fixed and known; (v) For simplicity, the system being analyzed considers the coexistence of non-QSTAs and QSTAs carrying the traffic of one AC only, i.e. the coexistence of non-QSTAs with QSTAs carrying voice, video, best effort or back ground traffic respectively; (vi) Only one fixed-size data frame is transmitted in each transmission.

A. Discrete time two-dimensional Markov chains

Fig. 1-3 illustrate the proposed two-dimensional discrete time Markov chain models: the model in Fig. 1 is used to model the channel contention procedure of a non-QSTA; the model in Fig. 2 is for a QSTA carrying voice or video traffic, because their IFS_E is equal to IFS_D ; the one in Fig. 3 is for a QSTA carrying best effort or background traffic, because their IFS_E is larger than IFS_D .

There are two stochastic processes within each Markov chain model. The first process, $u(t)$, represents the value of the backoff counter. Here a special value of $u(t) = -1$ is used to represent a transmission from the given station, which starts when the channel turns busy and ends when the idle IFS_D interval after the busy channel is completed³. The second process, $v(t)$, indicates the station's status. Here $v(t) = 0$ represents that the station is in a normal backoff procedure or it is transmitting. $v(t) = -1$ represents the station's backoff procedure is being interrupted by a transmission from other stations. $v(t) > 0$ represents that the station is waiting the $v(t)^{th}$ idle time slot after the IFS_D .

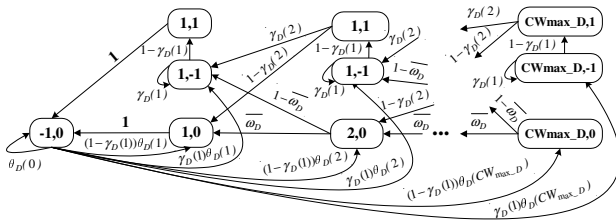


Fig. 1. The Markov chain model for a non-QSTA.

In Fig. 1, state $(k,0)$, $1 \leq k \leq CW_{max_D}$ represents an idle time slot in which a specific non-QSTA decreases its backoff counter to k . Here CW_{max_D} is the CW_{max} value for the non-QSTA. State $(k,-1)$, $1 \leq k \leq CW_{max_D}$ represents a transmission from other stations which interrupts the non-QSTA's backoff procedure. State $(k,1)$, $1 \leq k \leq CW_{max_D}$

³The reason why we includes the IFS_D in the transmission duration is that it is the smallest IFS in the system, and no transmission is possible in this interval. In the rest of this paper, this definition of a transmission duration is used.

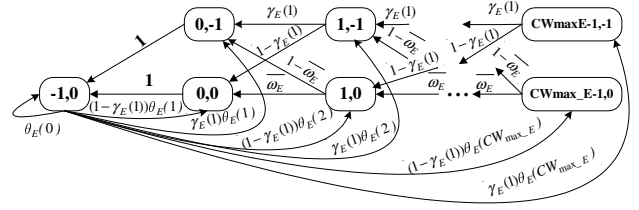


Fig. 2. The Markov chain model for a QSTA carrying voice or video traffic.

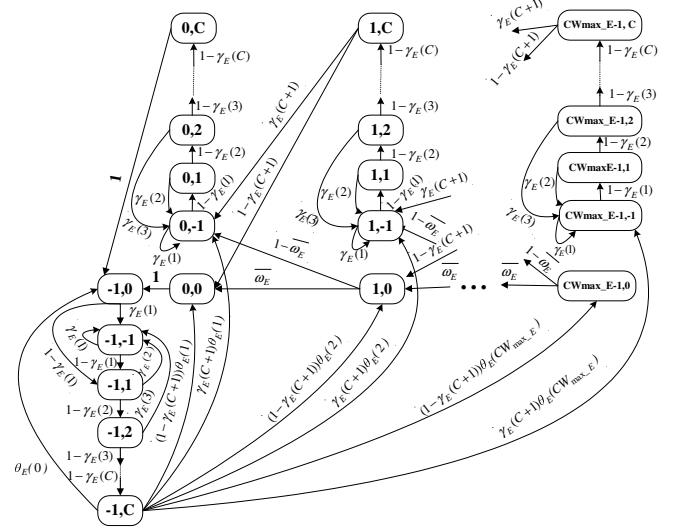


Fig. 3. The Markov chain model for a QSTA carrying best effort or background traffic.

represents an idle time slot immediately following a transmission from other stations. State $(-1,0)$ represents a transmission from the non-QSTA itself. The transition probability $\theta_D(k)$, $0 \leq k \leq CW_{max_D}$ represents that the non-QSTA starts a new backoff backoff procedure with an initial backoff counter k . The transition probabilities $\gamma_D(d)$ and $1 - \gamma_D(d)$, $d = 1, 2$ represent the channel status in the d^{th} time slot following a transmission: the channel turns busy with the probability $\gamma_D(d)$, or it remains idle with the probability $1 - \gamma_D(d)$. The transition probability $\bar{\omega}_D$ is the average probability that the channel remains idle in a time slot for the non-QSTA during its backoff procedure, and $1 - \bar{\omega}_D$ is the probability that the channel turns busy. State $(1,0)$ or $(1,1)$ represents the idle time slot immediately before the non-QSTA decreases its backoff counter to zero and start a transmission. After leaving the state $(1,0)$ or $(1,1)$, the non-QSTA will enter into state $(-1,0)$ to start a transmission with a probability of 1.

Slight differences exist in the Markov chains shown in Fig. 2 and Fig. 3, which represent the differences between DCF and EDCA described in Section I. The parameters $\theta_E(k)$, $\gamma_E(d)$, CW_{max_E} , and $\bar{\omega}_E$ have similar meaning as the corresponding terms $\theta_D(k)$, $\gamma_D(k)$, CW_{max_D} , and $\bar{\omega}_D$ in Fig. 1. The differences between the model for DCF and that for EDCA are:

First, following the end of IFS_E , the QSTA will decrease its backoff counter by one, while a non-QSTA must wait one extra time slot after the IFS_D . Therefore, no special state is required in Fig. 2 and Fig. 3 to represent the time slot after the IFS_E . Moreover, after completing the IFS_E following the QSTA's own transmission, the QSTA shall reach state $(k-1, 0)$ or $(k-1, -1)$ if it starts a new backoff procedure with a non-zero initial backoff counter k , while a non-QSTA shall reach state $(k, 0)$ or $(k, -1)$ if it has a non-zero initial backoff counter k .

Second, state $(0, g)$ ($g = 0, -1$ in Fig. 2 and $-1 \leq g \leq C$ in Fig. 3) is used to represent the channel contention procedure of the QSTA when its backoff counter has been decreased to zero. These states do not exist in the Markov chain shown in Fig. 1 because a non-QSTA shall start a transmissions immediately once its backoff counter reaches zero.

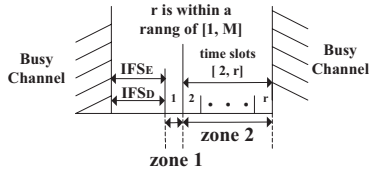
Finally, the Markov chain shown in Fig. 3 is used for a QSTA with an IFS_E larger than IFS_D . State (k, g) , $-1 \leq k \leq CW_{max_E}$, $1 \leq g \leq C$ ($C = AIFS - DIFS$) in the chain is used to represent the g^{th} idle time slot following a transmission, which is still within the IFS_E interval.

As the state $(-1, 0)$ in each Markov chain represents the station's own transmission, its steady-state probability is equal to τ_D (in Fig. 1) or τ_E (in Fig. 2 and Fig. 3) respectively, which needs to be solved.

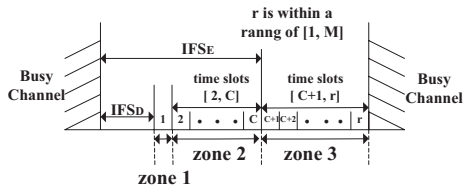
B. The zone specific transmission probability

Before we investigate the aforementioned Markov chains in further detail, we shall analyze the so-called zone specific transmission probability [5] in this section, which will be helpful for our further analysis.

Fig. 4 illustrates the time slots between two successive transmissions in the system being analyzed. Fig. 4(a) considers



(a) A system in which non-QSTAs and QSTAs carrying voice or video traffic coexist.



(b) A system in which non-QSTAs and QSTAs carrying best effort or background traffic coexist.

Fig. 4. Time slots between two successive transmissions in the system.

a system where non-QSTAs coexist with QSTAs carrying

voice or video traffic, for which $IFS_D = IFS_E$. Here the maximum number of the possible consecutive idle time slots between two successive transmissions in the system is bounded by M , where $M = \min(CW_{max_D}, CW_{max_E})$. As shown in Fig. 4(a), no transmission is possible in the IFS_D immediately following the busy channel. In the first time slot after the IFS_D , referred to as zone 1, non-QSTAs which get involved in the previous transmission, as well as QSTAs, may start a transmission. The transmission probability in this zone is thus given by

$$\beta(1) = \sum_{i=0}^{N_D} \{ [1 - (1 - \tau_D)^i (1 - \tau_E)^{N_E}] \phi(i) \}, \quad (1)$$

where $\phi(i) = \binom{N_D}{i} \tau_D^i (1 - \tau_D)^{N_D-i}$ represents the probability that i out of N_D non-QSTAs get involved in the previous transmission. In the remaining time slots, referred to as zone 2, all non-QSTAs and QSTAs may start a transmission. The transmission probability in zone 2 can be obtained by

$$\beta(2) = 1 - (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E}. \quad (2)$$

Fig. 4(b) considers a system where non-QSTAs coexist with QSTAs carrying best effort or background traffic, for which $IFS_E \geq IFS_D$ and $M = \min(CW_{max_D}, C + CW_{max_E})$. For ease of illustration, we consider that $C \geq 2$. Also it is not possible that a transmission occurs in the IFS_D after the busy channel. In the first time slot after the IFS_D , referred to as zone 1, only non-QSTAs which get involved in the previous transmission may start a transmission. In the time slots $[2, C]$, referred to as zone 2, all non-QSTAs may start a transmission. In the remaining time slots, referred to as zone 3, all non-QSTAs and QSTAs may transmit. The corresponding zone specific transmission probabilities can be obtained by

$$\begin{cases} \beta(1) = \sum_{i=0}^{N_D} \{ [1 - (1 - \tau_D)^i] \phi(i) \}, \\ \beta(2) = 1 - (1 - \tau_D)^{N_D}, \\ \beta(3) = 1 - (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E}. \end{cases} \quad (3)$$

From Fig. 4, a new discrete time one-dimensional Markov chain can be created, which is shown in Fig. 5. The stochastic process in this Markov chain represents the number of consecutive idle time slots between two successive transmissions in the system. The state (r) in the Markov chain model represents the r^{th} consecutive idle time slot from the end of the previous transmission in the system. The transition probability β_{-r} represents the corresponding zone specific transmission probability $\beta(k)$ after the r^{th} idle time slot following the previous transmission⁴, given in (1)-(3). State (M) represents the M^{th} idle time slot, and a transmission will occur immediately after it. Therefore the system will move from state (M) to state (0) with a probability 1. The steady state probability $s(r)$ for this Markov chain can be easily obtained,

⁴The similar symbol will be applied to other terms in the rest of this paper, including ρ_{D-r} , ρ_{E-r} , ω_{D-r} , ω_{E-r} , ψ_{D-r} , ψ_{E-r} , ϵ_{-r} , and ϱ_{-r} . They also represent the corresponding zone specific probabilities after the r^{th} idle time slot following the previous transmission.

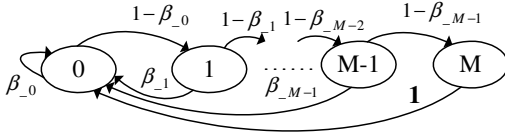


Fig. 5. The Markov chain model for modeling the number of consecutive idle time slots between two successive transmissions in the system.

and its expression is not given in in this paper due to length limitation. With the solution of $s(r)$, we may go further to analyze each system in detail.

C. The system of non-QSTAs and QSTAs carrying voice or video traffic

1) *Average collision probabilities, $\overline{\rho_D}$ and $\overline{\rho_E}$* :⁵ According to Fig. 4(a), in zone 1, for a non-QSTA, only other non-QSTAs which get involved in the previous transmission and QSTAs may transmit and cause a collision. In zone 2, all other non-QSTAs and QSTAs may transmit and cause a collision. Thus the collision probability for a specific non-QSTA should be zone specific, which can be obtained by

$$\begin{cases} \rho_D(1) = \sum_{i=0}^{N_D-1} \{ [1 - (1 - \tau_D)^i (1 - \tau_E)^{N_E}] \xi(i) \}, \\ \rho_D(2) = 1 - (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \end{cases}$$

where $\xi(i) = \binom{N_D-1}{i} \tau_D^i (1 - \tau_D)^{N_D-1-i}$ represents the probability that i out of the remaining $N_D - 1$ non-QSTAs get involved in the previous transmission. For a QSTA, the zone specific collision probability is given by

$$\begin{cases} \rho_E(1) = \sum_{i=0}^{N_D} \{ [1 - (1 - \tau_D)^i (1 - \tau_E)^{N_E-1}] \phi(i) \}, \\ \rho_E(2) = 1 - (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E-1}. \end{cases}$$

Thus, the corresponding average collision probabilities can be obtained as the sum of the weighted contention zone specific collision probabilities:

$$\begin{cases} \overline{\rho_D} = \sum_{r=0}^M [s(r) \rho_{D-r}], \\ \overline{\rho_E} = \sum_{r=0}^M [s(r) \rho_{E-r}]. \end{cases} \quad (4)$$

2) *The average probabilities that the channel remains idle in a time slot, $\overline{\omega_D}$ and $\overline{\omega_E}$* : For a non-QSTA in the backoff counter decrement procedure, it sees an “idle” time slot when no other stations start a transmission in the same time slot. The zone specific probability that a non-QSTA sees an idle time slot is then given by

$$\begin{cases} \omega_D(1) = \sum_{i=0}^{N_D-1} [(1 - \tau_D)^i (1 - \tau_E)^{N_E} \xi(i)], \\ \omega_D(2) = (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}. \end{cases}$$

For a QSTA, we can obtain the zone specific probabilities as

$$\begin{cases} \omega_E(1) = \sum_{i=0}^{N_D} [(1 - \tau_D)^i (1 - \tau_E)^{N_E-1} \phi(i)], \\ \omega_E(2) = (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E-1}. \end{cases}$$

⁵The average collision probabilities are not used in the proposed Markov chains directly, but they will be used to obtain transition probabilities in the Markov chains.

Thus, the corresponding average probabilities can also be obtained as the sum of the weighted contention zone specific collision probabilities:

$$\begin{cases} \overline{\omega_D} = \sum_{r=0}^M [s(r) \omega_{D-r}], \\ \overline{\omega_E} = \sum_{r=0}^M [s(r) \omega_{E-r}]. \end{cases}$$

3) *The transition probabilities, $\gamma_D(d)$ and $\gamma_E(d)$* : The Markov chains shown in Fig. 1 and 2 are used for this system, where $\gamma_D(d)$, $d=1, 2$ and $\gamma_E(1)$ are used.

According to Fig. 4(a), the 1st time slot and the 2nd time slot after the IFS_D are located in zone 1 and zone 2 respectively, and the 1st time slot after the IFS_E is located in zone 1, therefore we can have

$$\begin{cases} \gamma_D(1) = \sum_{i=0}^{N_D-1} \{ [1 - (1 - \tau_D)^i (1 - \tau_E)^{N_E}] \xi(i) \}, \\ \gamma_D(2) = 1 - (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \\ \gamma_E(1) = \sum_{i=0}^{N_D} \{ [1 - (1 - \tau_D)^i (1 - \tau_E)^{N_E-1}] \phi(i) \}. \end{cases}$$

4) *The probabilities that a station obtains an initial backoff counter k , $\theta_D(k)$ and $\theta_E(k)$* : Due to length limitation, just $\theta_D(k)$ is analyzed in this paper. A new Markov chain is created to model the number of transmission attempts of a non-QSTA for sending a data frame, as shown in Fig. 6.

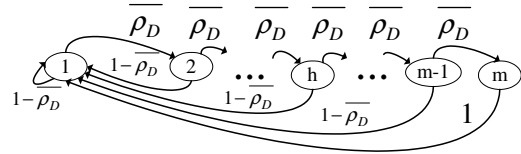


Fig. 6. The Markov chain for modeling the number of transmission attempts of a non-QSTA for sending a data frame.

In this Markov chain, h is the number of transmission attempts for sending a data frame by which the range $[0, CW_{max_D}]$ is firstly used, m is the maximum number of transmission attempts for sending a data frame, and $\overline{\rho_D}$ is the average collision probability for a non-QSTA, which is obtained in (4). Each state (y) represents the y^{th} transmission attempt of a non-QSTA for sending a data frame. We can easily obtain the steady state probability $d(y)$, which represents the probability that the y^{th} transmission attempt is implemented for sending a data frame. Due to length limitation, the expression of $d(y)$ is not given in this paper.

Therefore, the probability $\theta_D(k)$ that a non-QSTA station obtains an initial backoff counter value k can be obtained by

$$\theta_D(k) = \sum_{y=1}^m \frac{d(y)c(k)}{CW(y) + 1},$$

where $CW(y)$ is the CW value for the y^{th} transmission attempt for sending a data frame, which should follow the exponential increasing rule defined in IEEE 802.11 standard. $c(k)$ is equal to either 1 or 0. $c(k) = 1$ represents that the value k is included in the range $[0, CW(y)]$, otherwise it is not included.

D. The system of non-QSTAs and QSTAs carrying best effort or background traffic

Based on the description about zone specific transmission probability in Section II-B, we can easily solve the corresponding zone specific probabilities for a non-QSTA in the system shown in Fig. 4(b):

$$\begin{cases} \rho_D(1) = \sum_{i=0}^{N_D-1} \{ [1 - (1 - \tau_D)^i] \xi(i) \}, \\ \rho_D(2) = 1 - (1 - \tau_D)^{N_D-1}, \\ \rho_D(3) = 1 - (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \\ \omega_D(1) = \sum_{i=0}^{N_D-1} [(1 - \tau_D)^i \xi(i)], \\ \omega_D(2) = (1 - \tau_D)^{N_D-1}, \\ \omega_D(3) = (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \end{cases}$$

and we may obtain the average probabilities accordingly:

$$\begin{cases} \bar{\rho}_D = \sum_{r=0}^M [s(r) \rho_{D-r}], \\ \bar{\omega}_D = \sum_{r=0}^M [s(r) \omega_{D-r}]. \end{cases}$$

According to Fig. 4(b), a QSTA's backoff procedure is implemented in zone 3 only, where all other stations may transmit. Therefore we can obtain

$$\begin{cases} \bar{\rho}_E = 1 - (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E-1}, \\ \bar{\omega}_E = (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E-1}, \end{cases}$$

Accordingly, other transition probabilities can be obtained by

$$\begin{cases} \gamma_D(1) = \sum_{i=0}^{N_D-1} [1 - (1 - \tau_D)^i] \xi(i), \\ \gamma_D(2) = 1 - (1 - \tau_D)^{N_D-1}, \end{cases}$$

and

$$\begin{cases} \gamma_E(1) = \sum_{i=0}^{N_D} \{ [1 - (1 - \tau_D)^i] \phi(i) \}, \\ \gamma_E(k) = 1 - (1 - \tau_D)^{N_D}, 2 \leq k \leq C \\ \gamma_E(C+1) = 1 - (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E-1}. \end{cases}$$

Finally, $\theta_D(k)$ and $\theta_E(k)$ can be obtained by using the same approach described in Section II-C.4, and their expression is not given in this paper due to length limitation.

E. Summary

Finally, this section summarizes the relationship of earlier analysis.

- 1) In Section II-A, three novel Markov chains shown in Fig. 1-3 are created for each station category. In addition to τ_D and τ_E , other unknown transition probabilities are introduced, including $\theta_D(k)$, $\theta_E(k)$, $\gamma_D(d)$, $\gamma_E(d)$, $\bar{\omega}_D$, and $\bar{\omega}_E$.
- 2) In Section II-B, the zone specific transmission probability $\beta(k)$ is obtained in terms of τ_D and τ_E . A new Markov chain shown in Fig. 5 is created for each system being analyzed, and its steady state probability $s(r)$ can be obtained in terms of $\beta(k)$. Thus, $s(r)$ can also be obtained in terms of τ_D and τ_E .
- 3) In Section II-C and Section II-D, based on the results obtained in Section II-B, the unknown transition probabilities $\theta_D(k)$, $\theta_E(k)$, $\gamma_D(d)$, $\gamma_E(d)$, $\bar{\omega}_D$, and $\bar{\omega}_E$, can also be obtained in terms of τ_D and τ_E .

- 4) Now all unknown parameters have been expressed in terms of τ_D and τ_E . By considering the state relationship in the Markov chains shown in Fig. 1-3, each steady state probability can be expressed in terms of τ_D and τ_E . As the sum of a Markov chain's steady state probability should be equal to 1, one independent non-linear equation about τ_D and τ_E can be drawn from each Markov chain. Thus, a group of two non-linear equations can be obtained for each system being analyzed, and τ_D or τ_E can be solved.

III. SATURATED THROUGHPUT ANALYSIS

In this section, we shall analyze the saturated throughput. In each time slot between two successive transmissions in the system, one of the following four events may occur: (i) a successful transmission from a non-QSTA; (ii) a successful transmission from a QSTA; (iii) a collision; (iv) an idle time slot. According to Fig. 4(a) and Fig. 4(b), the corresponding zone specific probabilities for each system can be obtained by

$$\begin{cases} \psi_D(1) = \sum_{i=0}^{N_D} [i \tau_D (1 - \tau_D)^{i-1} (1 - \tau_E)^{N_E} \phi(i)], \\ \psi_D(2) = N_D \tau_D (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \\ \psi_E(1) = \sum_{i=0}^{N_D} [N_E \tau_E (1 - \tau_D)^i (1 - \tau_E)^{N_E-1} \phi(i)], \\ \psi_E(2) = N_E \tau_E (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E-1}, \\ \epsilon(k) = \beta(k) - \psi_D(k) - \psi_E(k), \\ \varrho(k) = 1 - \beta(k), k = 1, 2, \end{cases}$$

and

$$\begin{cases} \psi_D(1) = \sum_{i=0}^{N_D} \{ [i \tau_D (1 - \tau_D)^{i-1}] \phi(i) \}, \\ \psi_D(2) = N_D \tau_D (1 - \tau_D)^{N_D-1}, \\ \psi_D(3) = N_D \tau_D (1 - \tau_D)^{N_D-1} (1 - \tau_E)^{N_E}, \\ \psi_E(1) = 0, \\ \psi_E(2) = 0, \\ \psi_E(3) = N_E \tau_E (1 - \tau_D)^{N_D} (1 - \tau_E)^{N_E-1}, \\ \epsilon(k) = \beta(k) - \psi_D(k) - \psi_E(k), \\ \varrho(k) = 1 - \beta(k), k = 1, 2, 3, \end{cases}$$

respectively, where $\psi_D(k)$ and $\psi_E(k)$ are the probabilities that a successful transmission from a non-QSTA and a QSTA respectively occurs in a time slot in zone k, $\epsilon(k)$ is the probability that a collision occurs in a time slot in zone k, $\varrho(k)$ is the probability that no transmission occurs in a time slot in zone k, and $\beta(k)$ is the zone specific transmission probability given in (1) - (3).

Therefore, the average effective payload for non-QSTAs or QSTAs between two successive transmissions in the system can be obtained by

$$\begin{cases} E[DCF] = \sum_{r=0}^M [\psi_{D-r} s(r) P], \\ E[EDCA] = \sum_{r=0}^M [\psi_{E-r} s(r) P], \end{cases}$$

where $s(r)$ is the steady state probability for the Markov chain shown in Fig. 5, and P is the payload size of a data frame, which is considered as a known constant.

The average time duration between two successive transmission can be obtained as:

$$L = \sum_{r=0}^M \{s(r)[(\psi_{D-r} + \psi_{E-r})Ts + \epsilon_{-r}Tc + \varrho_{-r}TimeSlot]\},$$

where Ts and Tc are time required for a successful transmission and a collision respectively, which can also be considered as known constants.

Finally, the throughput for each station of each category can be obtained by

$$\begin{cases} Throughput_{DCF} = E[DCF]/L/N_D, \\ Throughput_{EDCA} = E[EDCA]/L/N_E. \end{cases}$$

IV. SIMULATION STUDY

The simulation study is carried out with OPNET [6]. The parameter setting of DCF and EDCA is as shown in Table-I, which is consistent with those defined in [7, Table 20df, p.49].

TABLE I
WLAN SIMULATION PARAMETER SETTING

Frame payload size	8000 bits
data rate	1Mbps
Maximum retransmission limit	7
DCF parameter set	$CW_{min} = 31, CW_{max} = 1023,$ $DIFS=SIFS+2TimeSlot$
EDCA voice parameter set	$CW_{min} = 7, CW_{max} = 15,$ $AIFS=DIFS$
EDCA video parameter set	$CW_{min} = 15, CW_{max} = 31,$ $AIFS=DIFS$
EDCA best effort parameter set	$CW_{min} = 31, CW_{max} = 1023,$ $AIFS=DIFS+TimeSlot$
EDCA background parameter set	$CW_{min} = 31, CW_{max} = 1023,$ $AIFS=DIFS+5TimeSlot$

Four scenarios are simulated, and each of them contains equal number of non-QSTAs and QSTAs of one traffic class. The results are shown in Fig. 7.

As shown in Fig. 7, the analytical results from the proposed model can generally agree well the simulation results, especially when the number of stations is large. However, a larger discrepancy between the analytical and the simulation results at smaller number of stations is observed. It results from the assumption used in the model, that is, the transmission probability at a generic time slot is constant. This assumption is more accurate when the number of stations is larger [8].

We observe the significant priority of EDCA voice or video over DCF, as well as that of DCF over EDCA background, which are caused by the large difference between their CW sizes or IFSs. A slight priority of DCF over EDCA best effort is also observed, which results from that IFS_D is one time slot shorter than IFS_E . It is obvious that traffic priority differentiation can still be implemented effectively in the coexistence condition. However, the results also imply that non-QSTAs may suffer a serious service starvation if they coexist with QSTAs carrying voice or video traffic.

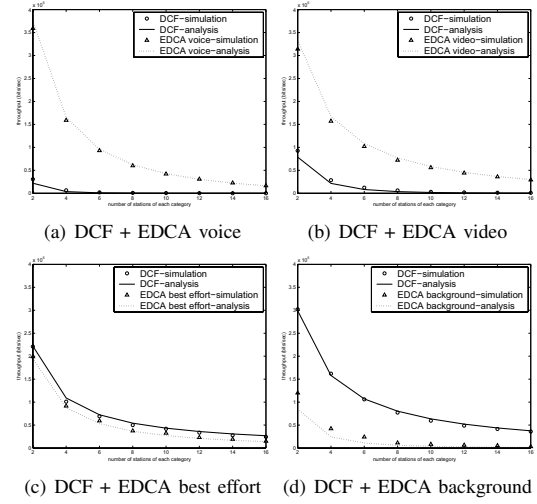


Fig. 7. Simulation and analytical results.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a novel Markov chain based analytical model for investigating the coexistence performance of DCF and EDCA. Some important factors were considered in our analysis, including the CW size, the IFS, the backoff counter decrement rule, and the transmission timing when the backoff counter reaches zero. We also obtained the saturated throughput with the proposed model. The simulation study verified the accuracy of the proposed model. The results we observed indicated that traffic priority differentiation can still be effectively implemented in the coexistence environment, but non-QSTAs may suffer a serious service starvation by coexisting with QSTAs carrying high-priority traffic. However, only the simple scenarios are analyzed in this paper, and we consider that more complex and more practical coexistence scenarios should be analyzed in our future research for further investigation.

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