Performance Assessment of IEEE 802.11e EDCF Using Three-dimension Markov Chain Model

I-Shyan Hwang \(^1\) and Hsin-Hao Chang

Department of Computer Engineering and Science
Yuan-Ze University, Chung-Li, Taiwan, 32026

Abstract

The new standard IEEE 802.11e is specified to support quality-of-service in wireless local area networks (WLAN). Recent research related to the Enhanced distributed channel access (EDCA) performance is only analyzed on the contention window (CW), but ignore the effect of arbitration inter-frame spaces (AIFS) and retry limits. This paper aims at providing an analytical model that captures the operation of the AIFSs, contention window sizes and retry limits differentiation for the EDCA mechanism under saturation condition based on a three-dimension Markov Chain model. The analytical model provides an in-depth understanding and insights into the EDCA protocol, and effectiveness of different parameters on the system performance is investigated through extensive numerical and simulation results.

Keywords: WLAN, EDCA, CW, AIFS, Three-dimension Markov Chain, Performance analysis.

1 Introduction

In the past, access networks in telecommunications or computer networks were mainly based on fixed wired access, making the device quite immobile. However, during the past few years, there has been a “boom” in the area of wireless access networks. Because of low cost, ease of deployment and mobility support, IEEE 802.11 WLANs have been used so widely that becomes the dominating wireless local area network technology. WLANs are becoming ubiquitous and increasingly relied on as IEEE 802.11 products become successful in the market. IEEE 802.11 medium access control (MAC) employs a mandatory contention-based channel access function called the distributed coordination function (DCF) and an optional centrally controlled channel access function

\(^1\)ishwang@saturn.yzu.edu.tw
called the *point coordination function* (PCF). However, the current DCF is unsuitable for real-time multimedia applications with quality-of-service (QoS) requirements. Even though the PCF can provide some limited QoS support, it is barely implemented in today’s products due to its complexity and inefficiency for normal data transmission.

To overcome this, the IEEE 802.11 Working Group created Task Group E to design MAC layer QoS enhancements to the 802.11 standard. The centerpiece of the 802.11e standard [1] is the *hybrid coordination function* (HCF), which includes a contention-based HCF part and contention-free centrally controlled HCF part. The contention-based HCF part is called *Enhanced Distributed Coordination Function* (EDCF). The EDCF provides the differentiated and distributed access to the wireless medium for multiple user priorities by differentiating the inter-frame space, the initial windows size, the maximum windows size and medium occupancy limits.

Recently, most of the papers that analyze the EDCA performance only consider the contention window but ignore the Arbitration Inter Frame Space (AIFS). This paper aims at providing an analytical model that captures the operation of the AIFSs, contention window sizes and retry limits differentiation for the EDCA mechanism under saturation condition based on a three dimensional Markov Chain model.

This paper is organized as follows. Related works are investigated in the Section 2. The proposed analytical system model is presented in Section 3 and validation and simulation results are studied in section 4. Finally, we draw our conclusions in Section 5.

## 2 Related Works

In the recent years, some 802.11 DCF analytical evaluations [2–5] are proposed. We propose a new improved analytical model and provide following comparisons with other models as follows and are shown in Table 1.

- Our model assumes that there is a finite retransmission limit (retry limit) that is consistent with the IEEE 802.11e standards, since Bianchi’s model [2] assumed an infinite retry limit. Furthermore, our model can analyze a differentiation among ACs with different retry limits. It is reasonable for real-time multimedia traffic with sensitive delay requirements since retransmitted frames may be too late to be useful, and a smaller retry limit is appropriate. However, some non-real-time transmissions may need a larger retry limit to enhance reliable transmissions.

- Bianchi’s model [2] assumes that the backoff counter is always decremented during a busy slot. This assumption is not consistent with the
IEEE 802.11 standards since the backoff counter is frozen when a transmission is detected on the channel, and reactivated when the channel is sensed idle. This assumption will be revision in our model.

- Xiao [3] developed a model to analyze the contention window size differentiation in the EDCA mechanism and assumed equal AIFS of all traffic classes. However this model lacks the AIFS differentiation in the 802.11e standard.

- ZA’s model [4] assumed that after every successful transmission, a station can transmit if the medium is idle without entering the backoff stage. Therefore, ZA’s model introduces a non-backoff stage and this assumption is not consistent with the IEEE 802.11e standards.

In this paper, a three-dimension Markov chain model [2,5] is developed with different types of chains for the operation of the AIFS and CW differentiation of EDCA mechanism and validated by simulation. Based on this model, the system performance metrics are derived in terms of system throughput and dropping probability.

3 Analytical Model

The analytical model for the EDCA mechanism with the AIFS and CW differentiation is discussed in this section. For simplicity, each station only considers one access categories (AC) in the EDCA and each wireless station (WSTA) always has packets to transmit under saturation condition.

3.1 Discrete Time Markov Chain Model

In the model, the 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. Figure 1 shows the Markov Chain model for stations implementing the AC1 to AC3. At time $t$, state $(j, k)$ of a WSTA is defined as the backoff stage $j$ and the current value of its backoff window size $k \in (0, W_j - 1)$. In the beginning ($j = 0$), $k$ is uniformly chosen between $(0, W_0 - 1)$, where $W_0$ is the initial window size. When the WSTA enters the backoff stage $j$, the backoff window size is reinitialized to a random value between $(0, W_j - 1)$. The backoff window size is increased by the factor of 2 until it reaches the maximum value ($W_m$) in the $m$-th retransmission, and then it is frozen until the $m'$-th retransmission. After the $m'$-th retransmission, the backoff window size is reinitialized to $(0, W_0 - 1)$ no matter what this transmission is successful or failed. A WSTA can transmit packets when the backoff timer reaches 0 or it must wait. The condition collision probability $p_i (i = 0, 1, 2, 3)$ is the probability that a transmission gets collided and is
Figure 2 shows the Markov Chain model for stations implementing AC0. The state \((j, k, 1)\) is defined as the waiting states when the high priority WSTAs are in transmission, and the state \((j, k, 0)\) represents the backoff contention window counting down states for AC0. Therefore, a frame of AC0 needs to wait longer than that of AC1, AC2 and AC3 to transmit due to waiting for high priority transmission and higher contention windows. The \(q_1\) is the probability that AC0 is in counting down state and AC1, AC2 and AC3 are not in transmission state, and \(q_2\) is the probability that a slot time no transmission by any WSTAs. Here, the transition probabilities in Figure 1 (for AC1 to AC3) are summarized as follows:

\[
\begin{align*}
Pr[(0, k) \mid (j, 0)] &= \frac{(1 - p_0)}{W_0}, & \text{for } 0 \leq k \leq W_0 - 1 \text{ and } 0 \leq j \leq m', \\
Pr[(0, k) \mid (m', 0)] &= 1, & \text{for } 0 \leq k \leq W_0 - 1, \\
Pr[(j, k) \mid (j, k)] &= p_0, & \text{for } 1 \leq k \leq W_j - 1 \text{ and } 0 \leq j \leq m', \\
Pr[(j, k) \mid (j + 1)] &= 1 - p_0, & \text{for } 0 \leq k \leq W_j - 2 \text{ and } 0 \leq j \leq m', \\
Pr[(j, k) \mid (j - 1, k + 1)] &= \frac{p_0}{W_j}, & \text{for } 0 \leq k \leq W_j - 1 \text{ and } 1 \leq j \leq m'.
\end{align*}
\]

Let \(\pi_{j,k} = \lim_{t \to \infty} \mathbb{P}\{s(t) = j, b(t) = k\}, j \in (0, m'), k \in (0, W_j - 1)\) be the stationary distribution of the chain, denoting the limiting probability of WSTA in state \((j, k)\). In steady state, it can be derived in a closed-form solution as follows:

\[
\pi_{j,0} = \pi_{j-1,0} \cdot p_i,
\]

where \(1 \leq j \leq m'\) and \(i = 1, 2, 3\). Then, it yields the following \(\pi_{j,0} = \pi_{0,0} \cdot p_i^j\).
1 ≤ j ≤ m’. The probability \( \pi_{j,k} \) for 0 ≤ j ≤ m’, can be given as follows

\[
\pi_{j,k} = \frac{W_j - k}{W_j} \cdot \frac{1}{1 - p_i} \pi_{j,0}, \quad 0 \leq j \leq m', \quad 1 \leq k \leq W_j - 1
\]

and

\[
\sum_{j=0}^{m'} \sum_{k=0}^{W_j-1} \pi_{j,k} = 1,
\]

where \( b_{0,0} = \frac{1}{\sum_{j=0}^{m'} \left[ \frac{W_j}{2} - \frac{1}{1 - \pi_{j,0}} \right]}. \)

Similarly, let \( \omega_{j,k,l} \) be the stationary distribution of the chain shown in Figure 2 for AC0. Then, we have \( \omega_{j,0,0} = \omega_{j-1,0,0} \cdot p_0, \) 1 ≤ j ≤ m’. Owing to the chain regularities, the transition probabilities in Figure 2 for AC0 is summarized as follows

\[
\omega_{j,k,0} = \frac{W_j - k}{W_j} \cdot \omega_{j,0,0}, \quad 0 \leq j \leq m', \quad 0 \leq k \leq W_j - 1,
\]

\[
\omega_{j,k,1} = \frac{W_j - k - (W_j - k - 1) q_2}{W_j q_1} \cdot \omega_{j,0,0}, \quad 0 \leq j \leq m', \quad 0 \leq k \leq W_j - 1,
\]

and \( \sum_{j=0}^{m'} \sum_{k=0}^{W_j-1} \sum_{l=0}^{1} \omega_{j,k,l} = 1, \) then

\[
\omega_{0,0,0} = \frac{1}{\sum_{j=0}^{m'} \left[ \frac{-W_j}{2} + \frac{W_j (q_2 - 1)}{2 q_1} + \frac{1 - q_2}{q_1} + \frac{q_2}{W_j q_1} + 1 \right] p_0}
\]

Let \( \tau_i \) be the probability in the states that the backoff timer reaches zero, which is expressed as \( \sum_{j=0}^{m'} p(j, 0, 0), \) and can be obtained as follows

\[
\tau_i = \begin{cases} 
\frac{\sum_{j=0}^{m'} \omega_{j,0,0}}{p_{idle}} = \frac{(1 - p_i^{m'+1}) \omega_{0,0,0}}{(1 - p_i) p_{idle}}, & i = 0 \\
\sum_{j=0}^{m'} \pi_{j,0} = \frac{(1 - p_i^{m'+1}) \pi_{0,0}}{1 - p_i}, & i = 1, 2, 3
\end{cases}
\]

The probability \( \tau_0 \) is conditioned probability that the previous slot is an idle slot as transmissions by AC0 stations. The channel idle probability \( p_{idle} \) can be calculated as \( p_{idle} = q_1 (1 - p_{idle}) + q_2 p_{idle} = \frac{q_1}{1 + q_1 - q_2}. \) A failed transmission is occurred due to receive the error packet or transmitted frame collides since one more stations transmit during a slot time. The probability \( p_i \) that ACi station encounters a collision, which is given by

\[
p_i = \begin{cases} 
1 - (1 - \tau_i)^{m_i - 1} (1 - p_{er}) \prod_{x \neq i} (1 - \tau_x)^{n_x}, & i = 0 \\
(1 - (1 - \tau_i)^{m_i - 1} \prod_{x \neq i, 0} (1 - \tau_x)^{n_x}) (1 - p_{er}) (1 - p_{idle}) \\
+ (1 - (1 - \tau_i)^{m_i - 1} \prod_{x \neq i} (1 - \tau_x)^{n_x}) (1 - p_{er}) p_{idle}, & i = 1, 2, 3
\end{cases}
\]
The model not only considers the collision effect, but also takes account of the packet error. The probabilities in terms of \( p_1, p_2 \) and \( p_3 \) are conditioned on whether the previous slot is busy slot or an idle slot. This is because the number of stations that can compete on the two cases is different. If the previous slot is a busy slot, only stations of AC1, AC2 and AC3 can transmit on the current slot as stations of AC0 need to wait for an extra slot time for a chance to transmit. The probabilities \( q_1 \) is the states that AC0 is in counting down state and AC1, AC2 and AC3 are all not in transmission state and \( q_2 \) is the probability that a slot time no transmission by any WSTAs, respectively, are

\[
q_1 = \prod_{i=1}^{3} (1 - \tau_i)^{n_i} \quad \text{and} \quad q_2 = \prod_{i=0}^{3} (1 - \tau_i)^{n_i},
\]

where \( n_i (i = 0, 1, 2, 3) \) denote the number of stations in the priority AC0 to AC3.

### 3.2 Throughput Analysis

Let \( P_{S,i} \) denote the probability that a successful transmission occurs in a slot time by a station of class AC\( i \) are given by

\[
P_{S,i} = \begin{cases} 
    n_i \tau_i (1 - \tau_i)^{n_i-1} \prod_{x \neq i} (1 - \tau_x)^{n_x}, & i = 0 \\
    n_i \tau_i (1 - \tau_i)^{n_i-1} \prod_{x \neq i, 0} (1 - \tau_x)^{n_x} (1 - P_i) \\
    + n_i \tau_i (1 - \tau_i)^{n_i-1} \prod_{x \neq i} (1 - \tau_x)^{n_x} P_{Idle}, & i = 1, 2, 3
\end{cases}
\]

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

The normalized system throughput \( S \) is defined as the fraction of time the channel is used to transmit packet payload successfully. A slot time can be idle or sensed busy due to (1) a successful transmission; (2) a collision and (3) an error frame. The probability of an empty slot is \( P_{Idle} \), and the probabilities, \( (1 - P_{Idle}) \cdot P_S \cdot (1 - p_{er}) \), \( (1 - P_{Idle}) \cdot (1 - P_S - P_{Idle}) \) and \( (1 - P_{Idle}) \cdot p_{er} \cdot P_S \) are a successful transmission, a collision, an error frame, respectively. Let \( \sigma, L, T_S, T_C, T_e, \) and \( H \) denote the duration of an empty slot time, the average payload packet size, the average time that the channel is sensed busy because of a successful transmission, the average time that the channel has a collision, the average time the channel is sensed busy due to an error transmission, and \( PHY_{hdr} + MAC_{hdr} \), respectively. Assuming that all packets are of the same size, the \( S \) can be expressed in the following

\[
S = \frac{(1 - P_{Idle}) \cdot P_S \cdot (1 - p_{er}) \cdot L}{P_{Idle} \cdot \sigma + (1 - P_{Idle}) \cdot P_S \cdot (1 - p_{er}) \cdot T_S + (1 - P_{Idle}) \cdot (1 - P_S - P_{Idle}) \cdot T_C + (1 - P_{Idle}) \cdot p_{er} \cdot P_S \cdot T_e}.
\]
Then, the three values $T_s$, $T_c$, $T_e$, are obtained for the basic mode and the RTS/CTS mode as follows:

**Basic Mode:**
\[
\begin{align*}
T_s &= H + L + \delta + SIFS + ACK + AIFS_{\text{min}} + \delta \\
T_c &= H + L + AIFS_{\text{min}} + \delta \\
T_e &= T_c
\end{align*}
\]

**RTS/CTS Mode:**
\[
\begin{align*}
T_s &= \text{RTS} + \delta + SIFS + CTS + \delta + SIFS + H + L + \delta \\
&\quad + SIFS + ACK + AIFS_{\text{min}} + \delta \\
T_c &= \text{RTS} + AIFS_{\text{min}} + \delta \\
T_e &= T_c
\end{align*}
\]

### 3.3 Frame Dropping Probability

A frame can be dropped only in state $(m', 0)$ and $(m', 0, 0)$ when the retransmission counter reaches the retry limit $m'$ from Figure 1 and Figure 2. It means that a frame encounter $m' + 1$ collisions. The probability $p_{\text{drop}}$ is given by $p_{\text{drop}} = p^{m' + 1}$, where $p$ denotes the collision probability of AC0-3.

### 4 Simulation

In this section, the numerical results of the model are compared with simulation results using the NS2 [2]. Each wireless station is assumed to have one AC to transmit and have enough data to send to obtain the saturated throughput. Then, the performance of the EDCA is affected by the CW and the AIFS values of different ACs in RTS/CTS mechanism are investigated. For simplicity and without loss of generality, there are two active ACs in each station are assumed, one is AC3 with higher priority, and the other is AC0 with lower priority. All the parameters [2] used in the analytical model and simulations are based on the parameters summarized in Table 2.

The simulation environment is one access point located in the center of the rectangular of 130 m by 130 m. The maximum transmission range of the access point is set to 130 m for fully coverage and two types of traffic, voice (AC3) and FTP (AC0), are considered. The results in both basic and RTS/CTS modes are obtained with a 95% confidence level in a less than 2% variation form the mean.

#### 4.1 Validation of the analytical model

Figure 3 compares the simulation and numerical results of the normalized throughput of RTS/CTS mode for different number of stations in the network.
Table 2: System parameters used in model [2]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet payload</td>
<td>8192 bits</td>
</tr>
<tr>
<td>MAC header</td>
<td>272 bits</td>
</tr>
<tr>
<td>PHY header</td>
<td>192 bits</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits + PHY header</td>
</tr>
<tr>
<td>RTS</td>
<td>160 bits + PHY header</td>
</tr>
<tr>
<td>CTS</td>
<td>112 bits + PHY header</td>
</tr>
<tr>
<td>Channel bit rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>Propagation delay</td>
<td>1 $\mu$s</td>
</tr>
<tr>
<td>Slot time</td>
<td>20 $\mu$s</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 $\mu$s</td>
</tr>
</tbody>
</table>

Figure 3: Validation of numerical and simulation results for normalized throughput.

with the following parameters: $CW[AC0] = [63–1023]$, $CW[AC3] = [0–63]$, Retry Limit[AC0, AC3] = [4, 7], AIFS[AC0, AC3] = [110 $\mu$s, 50 $\mu$s], and the number of stations $[N_{AC0} = N_{AC3}]$. The maximum deviation between numerical and simulation results is less than 5% in case of the numbers of station are $N_{AC0}=N_{AC3}=10$. The results show a high degree of correlation between the simulation and analytical model. In Figure 3, the AC3 always achieves higher throughput than the AC0. In addition, when the numbers of station for $N_{AC0}=N_{AC3}$ are increased, the throughput of AC3 is increased slightly and the throughput of AC0 decreases due to the AC3 always has a smaller delay since the CW is small. As the number of stations in the network increases, the throughput of AC3 remains relatively constant, while that of AC0 decreases by about 60%. Each AC has a longer backoff time and access delay when traffic is heavy, especially for the AC0.
Figure 4: Service differentiation effectiveness and effects for different AIFSs.

4.2 Effects of AIFS

In Figure 4, different AIFSs for AIFS[AC0] = 50 μs and AIFS[AC0] = 110 μs are employed to study the differentiation of AIFSs with the following parameters: CW[AC0] = [63–1023], CW[AC3] = [0–63], Retry Limit[AC0, AC3] = [4,7]. AIFS provides efficient service differentiation and preserves service to high priority traffic at high load. When the AIFS for AC3 and AC0 are equal, the throughput of AC3 has better performance than AC0 because the CW of AC3 is smaller than AC0. The result shows that when the AIFS of AC0 changes from 50 μs to 110 μs, the throughput of AC3 increases and AC0 decreases. The AIFS differentiation also speeds the backoff high priority stations, since these stations decrement their backoff counters faster than lower priority stations. Comparing with the light load and heavy load of Figure 4
Performance assessment of EDCF

Figure 6: Effects of different Retry limits with same CWs.

Figure 7: Effects of different Retry limits with different CWs.

(Number = 5, 30), the throughput of AC0 decreases slightly.

4.3 Effects of CW

Figure 5 shows the system throughput effects on different CWs of AC3 given the CW[AC0] = [127, 1023] with the following parameters: Retry Limit[AC0, AC3] = [4, 7], AIFS[AC0, AC3] = [110 μs, 50 μs], and the number of stations (N_{AC0} = N_{AC3}). As the CW of AC3 increases, the throughput of AC3 decreases, and the throughput of AC0 increases. When the CW of AC3 becomes smaller, AC3 gains more opportunities for transmission. Furthermore, the collision probability of AC0 is decreased so that the saturation throughput of AC0 will increase. It is interesting to notice that the throughput of AC3 is much
higher than that of AC0. Although the number of AC3 and AC0 increases, the throughput of AC3’s slope gets smooth-going. It implies that when the high priority of AC3 increases, the differentiation of effect of the CW size on the throughput becomes less and less significantly because most collisions occur among AC3.

4.4 Effects of Retry limit

Figure 6 shows the system throughput effects on different retry limits for different number of stations with the following parameters: $\text{CW}[\text{AC}0] = [0–1023]$, $\text{CW}[\text{AC}3] = [0–1023]$, $\text{Retry Limit}[\text{AC}0, \text{AC}3] = [4, 4–7]$, $\text{AIFS}[\text{AC}0, \text{AC}3] = [110 \mu s, 50 \mu s]$. The AC3 has the higher throughput than the AC0 when the retry limit of AC3 is smaller than that of AC0. It shows that the throughput will be quiet close to each other when the retry limit of AC3 and the $\text{CW}[\text{AC}3]$ is equal to the retry limit of AC0 and the $\text{CW}[\text{AC}0]$. The AC0 can gain the bandwidth from the AC3 when the retry limit of AC3 is increased, but the total throughput does not decrease.

For comparing the system throughput effects on different $\text{CW}[\text{AC}3]$s, the $\text{CW}[\text{AC}3] = [0–1023]$ is changed to $\text{CW}[\text{AC}3] = [0–63]$ shown in Figure 7. The throughput of AC3 is much higher than the throughput of AC0. In addition, when the numbers of station are increased, the throughput of AC3 is increased slightly and the throughput of AC0 decreases due to the AC3 always has a smaller delay since the CW is small. The throughput of AC3 with smaller CW is increased about 42% shown in Figure. 7 compared with that in Figure. 6.

5 Conclusions

In this paper, we have introduced a three dimension Markov model of the EDCA mechanism integrating the system parameters, AIFS and CW, under saturation condition. The results show a high degree of correlation between the simulation and analytical model. We also considered the retry limit and the consistent with the IEEE 802.11e standards. It is interesting to notice that the throughout affected by the CW is more significant than the AIFS, and the throughout affected by the AIFS is more significant than the retry limit.

References


Received: October 27, 2006