Performance Analysis of Transmissions Opportunity Limit in 802.11e WLANs

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Abstract
Transmission opportunity (TXOP) is a channel control mechanism introduced in the IEEE802.11e wireless LAN standard to improve channel utilization. In a previous paper, we have proposed a novel scheme to effectively predict the throughput of various TXOP classes based on a common threshold. In this paper, we extend this solution to incorporate the impact of the contention window (CW) size. We propose a novel concept employing different thresholds for individual classes controlled by CW and TXOP parameters under both Basic and RTS/CTS access modes. We use analytical modeling and simulations to investigate the individual and aggregate throughput based on the condition of thresholds. Our analytical models and simulation results indicate that the improved service differentiation and aggregate throughput can be achieved by exploiting TXOP and CW differentiation mechanisms compared to using TXOP mechanism only.

1. INTRODUCTION
Deployed wireless local-area networks (WLANs) often face the challenge of supporting diverse networked multimedia applications over a shared wireless medium. To meet this challenge, the IEEE 802.11 Task Group E proposed an enhanced MAC layer standard, called IEEE 802.11e, to provide service differentiation among WLAN users and applications. The 802.11e MAC supports two access methods, the contention-based Enhanced Distributed Channel Access (EDCA) and the centrally controlled Hybrid Coordinated Channel Access (HCCA). This paper considers the EDCA method since it is received most attention. Many techniques have been proposed to realize EDCA, but most of them are confined to the assignment of Arbitrary Interframe Space (AIFS) and backoff periods to different traffic classes. Another promising access priority scheme Transmission Opportunity Limit (TXOP) is proposed by IEEE 802.11e as an additional means to reduce contention and increase throughput. While existing literature focuses mostly on AIFS and backoff-based contention window as the main differentiation mechanisms, TXOP mechanism has received relatively little attention. In [1-3], the available results for TXOP are obtained based on simulation [1-3]. In [4], an analytical approach was proposed to evaluate TXOP operation by comparing different combination of the data bursting and block ACK mechanisms for a single TXOP category. While in [5], we have proposed a model to analyze the comparative throughput between different Access Categories as a function of different TXOP limits under both basic access and RTS/CTS modes. The influence of contention window differentiation was also evaluated by simulation, however, CW priorities have not been incorporated into TXOP analytical model.

In this paper, we proposed a model for analyzing the throughput of different access categories influenced by both TXOP limit and CW size values. Instead of employing a common TXOP threshold in [5], we derived different TXOP threshold as a function of TXOP limit and CW parameters to show that the choice of these parameters can lead to increased throughput for some ACs but reduced throughput for others. Another novel concept of our analysis is to employ total threshold to show how much the total throughput can be achieved. All our analytical results are validated by simulation. The rest of the paper is organized as follows, in section 2, we introduce the prioritized service specified in EDCA while in section 3 we analyze the backoff process related to contention window size to obtain the probability of channel access. Based on the probability, we derived the complete system model for TXOP under both access modes in section 3. The accuracy of our model is validated by simulation in section 4. Finally, in section 5, we conclude the paper.

2. DESCRIPTION OF PRIORITIZED SERVICE WITH EDCA
The EDCA mechanism provides priority service by the introduction of Access Categories (ACs). Each station supports four ACS and each AC associates an independent transmit queue. Each queue specified in the standard implements channel access function by adopting a combination of three different parameters: Arbitrary Interframe Spacing (AIFS), Contention Window Size and Transmission Opportunity (TXOP) duration. The mechanisms that employed to assign these parameters to users for service differentiation are named as AIFS differentiation, CW differentiation and TXOP differentiation mechanisms. In this paper, we focus on the later two mechanisms and fix AIFS parameters set for each AC one time slot.
The operation of the channel access function for EDCA is similar to DCF. Data transmission starts when the medium is found to be busy, the backoff timer (CW size) is set to an initial value of $[1, \text{CWmin}[AC]]$ slot time. The backoff timer reduces by a slot time each time when the channel is sensed idle and stops when the channel is busy. The timer is reactivated to decrement when the channel is idle for an AIFS plus a slot time. As soon as backoff timer reaches zero, the awaiting packet will get access to the channel and start transmitting. If a collision occurs, the CW size is chosen from $[1, \text{CWmin}[AC] \times 2^j]$. $i$ is the retransmission attempts the station has tried. After a successful contention, the channel access function employs TXOP to control the period to access the medium. Apart from CW size and AIFS period, TXOP allows initiating multiple frame exchange sequences between stations and access-point so that the aggregate throughput is improved. The total duration of the exchange is bounded by a maximum TXOP duration defined in TXOP limit(AC) as for per individual class, or access category (AC). Higher priority ACs usually would be configured with longer TXOP limits and smaller CWmin and CWmax size than lower priority classes. Longer TXOP limit means that the service class can transmit more frames and smaller CWmin and CWmax size means the service class is easier to access channel; hence better QoS are achieved.

3. BACKOFF MARKOV PROCESS

We employ a discrete time bidimensional Markov process based on Bianchi’s work [6] to model backoff and transmission for stations with a certain AC category. The contention window ranges from 1 to CW as referred to [7]. From this, we only illustrate the different formulas of our model from Bianchi’s model.

Denoting the stationary distribution of the backoff counter $k$ found in state $i$ in class $j$ as $b_j(i,k)$ and $W_i$ as contention window size, the largest backoff counter in stage $i$, $i$ range from 0 to $m$ where $\text{CWmax} = 2^m \text{CW}_{\text{min}}$, we note the following relationship between backoff states:

$$b_j(i,k) = p'_c \cdot b_{01}, \ i \in (0,m]$$

(1)

$$b_j(i,k) = \frac{W_i - k + 1}{W_i} \cdot p'_c \cdot b_{01}, \ i \in [0,m], k \in [1, W_i]$$

(2)

A solution for $b_j(i,k)$ in terms of average conditional collision probability $p_c$ is found by imposing the normalization condition on the Markov process,

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i} b_j(i,k)$$

(3)

Recalling our definition that transmissions occur whenever the backoff counter $k$ reaches zero, we find the probability $\tau_j$ that a station of category $j$ transmits during a randomly chosen slot time

$$\tau_j = \sum_{i=0}^{m} b_j(i,1).$$

(4)

A transmitted frame collides when more than one station also transmit during the same slot time. The probability that a station of class $j$ sends a frame but suffer collision is,

$$p_{ij} = 1 - \prod_{i=0}^{j-1} \frac{(1 - \tau_j)^{n_k}}{(1 - \tau_j)}$$

(5)

$n_k$ is the number of stations in class $k$. With (4) and (5), it is sufficient to form a close form nonlinear system and solve $p_{ij}$ and $\tau_j$ by numerical methods. The successful probability of any station $j$ access the channel can be expressed as,

$$p_{sj} = n_j \tau_j \prod_{i=0}^{j-1} \frac{(1 - \tau_j)^{n_k}}{(1 - \tau_j)}$$

(6)

4. TXOP ANALYTICAL MODEL

Let $s_j$ be the throughput obtained by Access Category $j$, or AC($j$), defined as the fraction of time the channel is used to successfully transmit frames; then

$$s_j = \frac{E[\text{payload transmitted in a transmission period}]}{E[\text{length of a transmission period}]}$$

(7)

Assuming there are $J$ access categories in the system, the system throughput $S$ is the sum of $s_j$, for $j \in [0, J-1]$. Let us divide the transmission duration into three different components: 1) successful transmit overhead $O_s$, (2) collision time overhead $O_c$ and (3) data transmission burst. We specify the values of these components for two different access modes: basic access and RTS/CTS access. Note that the physical frame header ($H_{\text{phy}}$) is always transmitted using the PHY layer basic rate $R_b$, while the payload, including MAC header ($H_{\text{mac}}$) and ACK packet are transmitted using the operational rate $R$ where $R \geq R_b$. Let $\delta$ be the propagation delay and SIFS be the duration of short interframe space, the values of $\delta$ and SIFS are given in the next section. For AC $j$, we can calculate $O_s$, $O_c$ in both basic-access mode ($O_{bas}$) and RTS/CTS ($O_{rts}$ and $O_{crts}$) as follows,

$$O_{bas} = O_{cbas} + AIFS_j, \quad \text{(basic access)}$$

$$O_{rts} = H_{\text{phy}} / R_b + \text{RTS} / R + 2\delta + 2\text{SIFS} + H_{\text{phy}} / R_b + \text{CTS} / R + \text{AIFS}$$

(8)

When the medium is determined to be available under EDCA access rule, the TXOP value is defined as the maximum limit for the data transmission duration. For a given access category $j$, $U_j$ is the duration of a transmission unit, defined as the time required to transmit an average payload (frame) of size $E[P_j]$. Therefore,

$$U_j = H_{\text{phy}} / R_b + (H_{\text{mac}} + E[P_j]) / R + \delta + \text{SIFS} + Ato$$

where $Ato = H_{\text{phy}} / R_b + \text{ACK} / R + \delta + \text{SIFS}$

(9)
The maximum data transmission duration for AC(j) is the product $TXOP = k_j U_j$, where $k_j$ is the number of transmission units, or the burst length (expressed in transmission units). In (2) and (3), RTS, CTS and ACK do not include the header size. Using $TXOP$, for AC(j), $k_j$ is obtained by,
\[ k_j = \frac{TXOP}{U_j}, \quad k_j \geq 1 \]  
(10)

According to IEEE 802.11 standard, during collision, each station waits for ACK timeout before starting a new transmission cycle. This is realized in our model by including ACK timeouts in (3) so that ACK timeout is included in the collision period. Let $p_s$ denote the success probability of channel access for AC(j), and let $P_s$ be the probability of a successful channel access by any category. Then, $P_s = \sum_{j=0}^{J-1} P_{sj}$, and the expected payload size in a transmission period is a function of $k_j$ as follows,
\[ E[P_j(k_j)] = p_s \cdot k_j \cdot E[P_j] \]  
(11)

For basic-access and RTS/CTS modes, the expected lengths of the transmission period are,
\[ T_{bas}(k_j) = O_{bas} + S + C \cdot T_{rs}(k_j) = O_{rs} + S \]  
(12)

In the above,
\[ O_{bas} = \sigma + \sum_{j=0}^{J-1} O_{bas,j} P_{sj} + (1 - P_j) \sum_{j=0}^{J-1} O_{bas,j} \]  
(13)
\[ O_{rs} = \sigma + \sum_{j=0}^{J-1} O_{rs,j} P_{sj} + (1 - P_j) \sum_{j=0}^{J-1} O_{rs,j} \]  
(14)
\[ S(k_j) = \sum_{j=0}^{J-1} P_{sj} k_j U_j \]  
(15)
\[ C(k_j) = (1 - P_j) \sum_{j=0}^{J-1} k_j U_j \]  
(16)
\[ U_j = H_{phy} / R_j + (H_{max} + E[P_j]) / R + \delta + \text{SIFS} + \text{Ato} \]  
(17)

In (17), we see that $U_j$ is obtained by replacing $E[P_j]$ with $E[P_j^*]$ in (7), $E[P_j^*]$ would be the longest average single payload of specific AC j involving in collision, in this way, we would have $U_j^{*} \geq U_j$ . $k^{*} U_j^{*}$ is the data frame containing the longest packet payload $k^{*} E[P_j^*]$ involved in a collision. Therefore, $k^{*} U_j^{*}$ would be no less than $k_j U_j$ . $\sigma$ is the duration of an empty slot time.

Let us suppose $p_{sj}^0$ and $p_{sj}^*$ are obtained by initial sets of CW and TXOP parameters. When the parameters related to access control such as CW change, they are changed to $p_{sj}^0$ and $p_{sj}^*$.

We define,
\[ A_{bas,j} = E^0[P_j(1)] O_{bas} \cdot A_{bas,j}^* = E^*[P_j(1)] O_{bas} \]  
(18)
Similarly, $A_{rs,j}^0 = E^0[P_j(1)] O_{rs}^0$ and $A_{rs,j}^* = E^*[P_j(1)] O_{rs}^*$. Further, we define,
\[ B_j^0 = C^+(k_j^*) E^0[P_j(1)] \cdot B_j^* = C^+(1) E^*[P_j(1)] \]  
(20)
\[ D_j^0 = S^+(k_j^*) E^0[P_j(1)] \cdot D_j^* = S^+(1) E^*[P_j(1)] \]  
(21)

In the above, $E^0[P_j(1)]$, $O_{bas}^0$, $O_{rs}^0$, $C_{bas}^0$ and $S^0$ are obtained by replacing $p_{sj}$ and $P_s$ with $p_{sj}^0$ and $P_s^0$ in (11), (13), (14) (15) and (16) respectively. $E^*[P_j(1)]$, $O_{bas}$, $O_{rs}$, $C_{bas}$ and $S^*$ are obtained in the same way. $E[P_j(1)]$, $C_{bas}$ and $S$ are given by setting $k_j$ in (11), (13), (14) (15) and (16) as 1 for all ACs for the case of no burst transmission. For $k_j > 1$, $C_{bas}(k_j)$ and $S(k_j)$ means that at least one category, AC(j), applied burst transmission.

It is complicate to find how the throughput would vary with the sets of TXOP and CW parameters since the current situation doesn’t just depend on TXOP value but on the channel access probability. However, after we define TXOP Threshold, we found it becomes easy. For basic access mode, the TXOP threshold is given by,
\[ Th_{bas} = (A_{bas,j}^0 + B_j^* + D_j^*)/(A_{bas,j}^0 + B_j^0 + D_j^0) \]  
(22)
And for RTS/CTS mode, it is,
\[ Th_{rts} = (A_{rts,j}^0 + B_j^* + D_j^*)/(A_{rts,j}^0 + B_j^0 + D_j^0) \]  
(23)

The conclusion we obtained is when $k_j < Th_{bas}$ or $k_j < Th_{rts}$, the throughput of category j decreases in basic access mode or RTS/CTS mode respectively, otherwise, their throughput increases.

The condition for total throughput is obtained by summing up TXOP threshold of all AC,
\[ Th_{total} = \sum_{j=0}^{J-1} Th_{bas,j} \cdot Th_{total} = \sum_{j=0}^{J-1} Th_{rts,j} \]  
(24)

Therefore, the total throughput are increased if $\sum_{j=0}^{J-1} k_j > Th_{total}$ for basic mode and $\sum_{j=0}^{J-1} k_j > Th_{total}$ for RTS/CTS mode.

Compare (15) and (16), since $k_j^{*} U_j^{*}$ is the longest period of single data transmission, $B$ in (20) containing $C$ would become a dominant factor to determine basic TXOP threshold, that is, a higher contention would result in a larger TXOP threshold in basic mode. However, since RTS/CTS don’t contain $B$ and the item $D$ are mainly determined by $S$ in (13), a higher contention would therefore result in a lower TXOP threshold.

These can be confirmed by following numerical results. The above analysis is obtained from modification of Bianchi’s model. However, as far as we know, the TXOP issue addressed in this paper has not been paid much attention in current literature. Additionally, the threshold obtained in (23) and (24) provide a useful method to predict the trends of achieved performance. Based on the threshold, we could control and optimize individual and overall system performance in our future work.
5. SIMULATION RESULTS

To validate our analytical model, we compare it with simulations conducted in NS-2.26 [8]. Unless otherwise specified, the values of the parameters used to obtain numerical results for both the analytical model and the simulation results, are summarized in Table 1.

All stations are configured according to the 802.11e system parameters and the specific AC parameters. Saturation conditions are created by using high constant bit rate traffic generators for all stations. The elastic traffic such as TCP is not considered as it has less QoS requirement than inelastic traffic. In all simulations, transmitting stations contend to transmit fixed size user datagram (UDP) packets to a single station (i.e., an access point). Therefore, the transmission unit period $U_j$ is constant for all access categories as defined in (3).

Table 1

| 802.11e SYSTEM PARAMETERS AND ACCESS CATEGORY PARAMETERS USING IN SIMULATION AND ANALYSIS |
|---------------------------------|----------------|
| Frame payload                   | 8000 bits      |
| MAC header                      | 224 bits       |
| PHY header                      | 192 bits       |
| ACK                              | 112 bits + PHY header |
| RTS                              | 160 bits + PHY header |
| CTS                              | 112 bits + PHY header |
| Channel bit rate                | 1 Mbit/s       |
| Payload bit rate                | 11 Mbit/s      |
| Propagation delay               | 1 µs           |
| Slot time                       | 20 µs          |
| SIFS                            | 10 µs          |
| ShortRetryLimit                 | 7              |
| CWmin[0-3]                      | 16             |
| CWmax[0-3]                      | 1024           |
| AIFS                            | SIFS + 2 × Slot time |
| Number of stations              | 5 (default)    |

Initially, we set the value of TXOP to default $U_j$ and set CW to the value in Table 1. We increase TXOP by 0, 1, 2, 3 and CWmin by 16, 32, 48 and 64 for AC[0], AC[1], AC[2] and AC[3] each time when the data is collected. The TXOP differences and CWmin differences therefore increases from 0 to 4 and 0 – 64 for five rounds of data collections. Note that the purpose we set more CWmin differences than TXOP is to see the results obtained by CW differentiation more clear. We evaluate CWmin and TXOP differentiation mechanisms separately in Fig. 1 and Fig. 2, and then compare them with the combined CWmin and TXOP differentiation mechanism in Fig.2. From these figures, we find that the throughput differences between each AC are increases with the increase of TXOP or CWmin differences. We first look at the influence of CWmin difference in Fig. 1 and TXOP difference in Fig. 2 (shown as Analysis TXOP in the legend). The gaps between each individual throughput differentiated by TXOP mechanism are shown smaller than by CW mechanism in Fig.2, higher priorities for example AC[3] obtains much better performance than lower priorities AC[2] and so on. The reason for this is that we use much bigger CWmin differences than TXOP differences among ACs. When using CW together...
with TXOP differentiation mechanisms, higher priorities (i.e. AC[3]) achieves much better performance in Fig. 2 than it achieves by using either CW differences in Fig. 1 or TXOP difference in Fig. 2 because of the differentiation effect of both mechanisms. The throughput of lower priorities (i.e. AC[0]) are even reduced by the combined TXOP and CWmin mechanisms in Fig. 2 as compared to CWmin differentiation in Fig. 1. These results were predicted very well by our calculation in (21) that has incorporate CW into TXOP analysis. Access Categories AC[0] and AC[1] have actual TXOP limit larger than its calculated threshold, therefore both throughput decrease in Fig.3. Fig.3 also shows that the throughput of AC[2] and AC[3] increase with TXOP value set less than their calculated threshold.

We next compare the total throughput performance for both basic access mode and RTS/CTS mode. Since the probability to obtain the channel access also depends on traffic load, we evaluate the total throughput by using TXOP differentiation mechanism at traffic loads of 5 and 30 contention stations as well as TXOP and CW differentiation at traffic loads of 5 stations. Fig. 4(a) shows that TXOP differentiation at number of 5 and 30 stations obtained higher total TXOP threshold from (22) than the actual TXOP settings in basic access mode, the corresponding aggregate throughput decreases as shown in Fig.5. In contrast, the total throughput in RTS/CTS mode increases in Fig.5 as the calculated TXOP threshold from (23) is smaller than the actual TXOP values shown in Fig.4(b). In addition, both Fig.4(a) and (b) show that the total calculated threshold for the combined CWmin and TXOP differentiation are below the actual TXOP value, their total throughput obtained in both access modes are thus increased in Fig.5. Compared with Fig.4(a) (b) and Fig.5, we also find that a higher total TXOP threshold corresponds to a lower achieved throughput in basic mode but a higher throughput in RTS/CTS mode because of the influence of
colliding payload on basic access mode.

6. CONCLUSIONS

We have proposed a model to estimate TXOP transmission performance and the impact of the CW and offered traffic load for both basic and RTS/CTS mode. We have used analytical modeling and validated our results using simulations. The following three points summarize our conclusions.

First, our analytical model and simulation results lead us to conclude, the individual and total threshold set, defined in (22) (23) and (24) are accurate to predict the throughput increment/decrement of each individual class and the aggregate throughput variation. Specialy, in basic access mode which is in contrast to RTS/CTS access mode, a higher total TXOP threshold results in a lower total throughput.

Second, we show that the TXOP enhancement obtained by individual class doesn’t necessarily lead to increased aggregate throughput. However, RTS/CTS mode would achieve better performance than Basic access mode and increasing traffic load would cause degraded performance. Finally, we show that incorporating CW difference into TXOP differentiation service can produce increased service differentiation as well as enhanced throughput performance.

REFERENCES