# Analysis of Burst Acknowledgement Mechanisms for IEEE 802.11e WLANs over Fading Wireless Channels

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*Abstract:* Transmission opportunity, or TXOP, is a channel control method introduced in the IEEE 802.11e wireless local area network (WLAN) standard. The control method includes some new operations developed for improving channel efficiency. In this paper, we propose an analytical model to evaluate these TXOP operations under fading channels. With this model, we calculate the maximum achievable throughput for the IEEE 802.11 DCF with RTS/CTS access mode. In addition, we quantify in the experiments how these operations can affect the system efficiency for different environments. The experiment results well confirm the theoretical model that provides new insights on design criterion for a WLAN in the real world.

*Key–Words:* WLAN, TXOP, Burst Transmission, Acknowledgment Aggregation, Performance Analysis.

## 1 Introduction

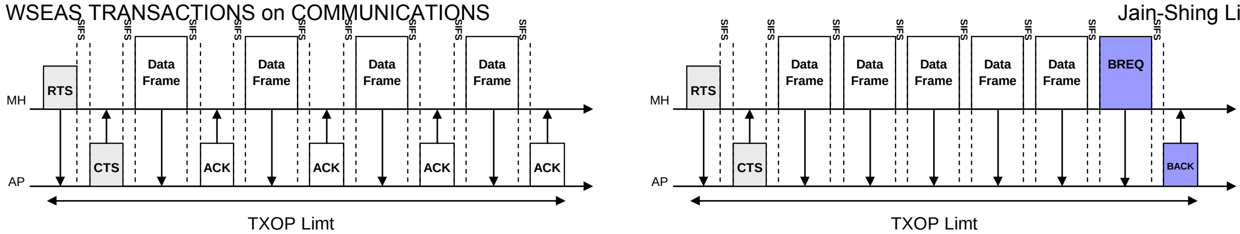
With the increasing deployment of WLANs in customer premises, came the challenge of supporting diverse networked multimedia applications over a shared wireless medium. Facing the challenge, the IEEE 802.11 Task Group E proposes an enhanced MAC layer standard, namely IEEE 802.11e [1], to provide service differentiation among WLAN users and applications. The 802.11e MAC defines two medium access schemes: contention-based Enhanced Distributed Channel Access (EDCA) and centrally controlled Hybrid Coordination Channel Access (HCCA). However, many research works only focus on EDCA because it is currently promoted by the majority of vendors. In particular, these works concentrate mainly on how to configure the WLAN parameters so as to achieve better service differentiation. The various proposals for realizing EDCA are confined to the assignment of Arbitrary Inter-frame Spacing (AIFS) value and Backoff periods to different traffic classes.

Additionally, IEEE 802.11 also provides means for increasing throughput and reducing contention through a prioritized access scheme called Transmission Opportunity (TXOP). This scheme increases aggregate system throughput by allowing multiple consecutive frame exchanges to take place between a station and access-point (AP). More precisely, two new operations, namely data transmission bursting and aggregated acknowledgments that can efficiently eliminate communication overheads in the legacy DCF, are standardized as part of the IEEE 802.11e MAC, which receives quite a lot of attentions. In this paper we consider these new operations performed under an error-prone channel. A modified Markov chain model of the back-off window is derived to account for both frame error probability and the maximal retransmission limit for each of the following methods that involve the new operations. These methods are 1) the Normal Acknowledgement (NA) method that involves only the transmission bursting, and 2) the Block Acknowledgement (BA) method that involves both transmission bursting and aggregated acknowledgments. For these methods, we derive their maximum throughputs with different frame error probabilities, TXOP limits, and the other parameters involved. Finally, in the experiments, we quantify the two methods by showing their effects on the system performance in different environments. Their results are shown to be very consistent with those of the theoretical analysis.

The paper is organized as follows. In Section 2, we briefly summarize the new operations of EDCA. In Sections 3 and 4, we calculate the maximum throughput for the NA method and the BA method, respectively. The theoretical results are examined in Section 5. The related works are summarized in Section 6, and finally, conclusions are drawn in Section 7.

## 2 IEEE 802.11e EDCA

As known widely, the IEEE 802.11e defines Enhanced Distributed Channel Access (EDCA) to provide d-




(a) (b)

Figure 1: Transmission with Normal ACK (NA) and Block ACK (BA): (a) the NA method, and (b) the BA method.

ifferential services among contending stations [1]. Specifically, there are two major operations of EDCA designed to improve the system efficiency. The first allows the probability of accessing the channel to be differentiable among stations. The second defines the transmission unit based on the channel access time. Given these operations, we focus on the innovative aspects of the burst transmission and the corresponding acknowledgment operations. That is, we focus on the fact that once a station succeeds in competing the channel, EDCA will give the station a TXOP for its data transmission and specify an ACK mechanism to response it. For reference, their characteristics are summarized as follows.

### 2.1 Transmission Opportunity

To enhance the system efficiency, EDCA allows a station wining the medium contention to gain a TXOP, defined by the starting time and the maximum duration of a transmission, with that the station can send one or more MPDUs in a burst, separated by SIFS and limited by a threshold, namely $TXOP\ limit$, to complete its channel access. Given this mechanism, fragmentation is mandatory whenever the MSDU transmission duration exceeds the TXOP limit.

### 2.2 Block Acknowledgment

To reduce the channel wastes caused by the ACK transmissions, EDCA also defines a new acknowledgment scheme that allows a block of MPDUs to be acknowledged by a final aggregated ACK frame, called *block ACK (BACK)*, and thus reducing the number of ACKs required by each data frame in a burst transmission. The block ACK contains information about the reception of the whole block of data frames through a bitmap. However, it will not be transmitted automatically after a burst of data transmission. Instead, it only begins after receiving an explicit transmission request, namely block ACK request, sent by the requester.

In addition, for quickly identifying collisions and reducing the possibility of other transmissions occurred during a TXOP, the head-of-burst (HOB) frame of each new burst transmission requires to be protected with an immediate acknowledgement. The mechanism can be done with the RTS/CTS exchange. That is, after successfully receiving a CTS frame, other stations are forbidden on the channel access during the period of time specified in the RTS/CTS duration fields.

### 2.3 NA and BA Methods

When these operations combined, two corresponding methods for the WLAN could be resulted. As shown in Fig. 1 (a), the method without BACK, namely the Normal Acknowledgment (NA) method, transmits its data frame once a time and waits an immediate ACK until reaching the TXOP limit. On the other hand, the method with BACK, namely Block Acknowledgement (BA) method, sends multiple back-to-back data frames, each separated by a SIFS period of time, and then issues a block ACK request (BREQ) to expect the receipt of the corresponding BACK, as shown in Fig. 1 (b).

## 3 Throughput Analysis for The NA Method

In this section, we first introduce a Markov chain model for the NA method, and then, based on this model, we calculate the method's maximum achievable throughput.

### 3.1 Markov Chain Model

In this work, we adopt a Markov chain model with a representation similar to that of [2], and also, make a similar assumption that the network consists of $N$ contending stations and each of them always has backlog packets to be transmitted. However, unlike that

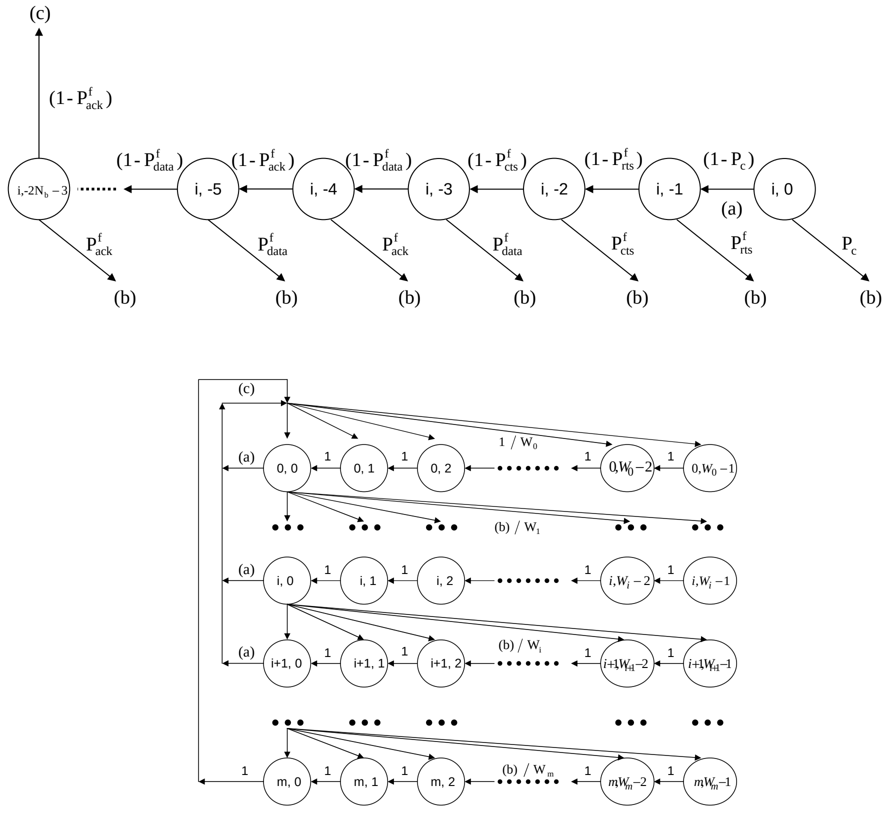



Figure 2: Markov chain model for the NA method

work, our model takes into account not only the back-off procedure, but also the new operations of EDCA (i.e., TXOP and block ACK), the frame error probability for each type of frame involved, and the maximal allowable number of retransmission attempts.

In addition, due to our analysis involving the frame error probability, we consider that 1) only RTS will suffer both collisions and frame errors while the other frames suffer only frame errors, and 2) if no response for a RTS/DATA/BREQ returns, the sender will timeout and invoke the binary exponential back-off (BEB) procedure. The first is made because a control frame should be transmitted with the maximum BSS basic rate equal to or lower than the data rate. In our work, a control frame is transmitted with the lowest rate to reach the most distant station in the WLAN and thus to robustly prevent collisions in the network[1]. The second is made because the BEB procedure will be invoked for the transmission fails, indicated by a failure to receive a CTS in response to an RTS, a failure to receive an ACK frame that was expected in response to a unicast MPDU, or failure to receive a BACK or ACK frame in response to a BREQ frame (referring to [1]). In such cases, a timeout period is required before invoking the BEB procedure.

The Markov chain model for the NA method is given in Fig. 2, which involves two halves. The bottom half represents the back-off procedure with the maximal allowable number of retransmission attempts of EDCA, $m$. When reaching this limit, a station will give up its current transmission and go to the first stage for the next transmission with probability of 1. On the other hand, the upper half represents the states after reaching the zero back-off count that accounts for the NA method. It denotes the fact that after reaching the state of 0 ( i.e., reaching the zero back-off count), the model can not decide its next back-off stage only according to the collision probability $P_c$. Instead, it should go through the states in the upper half that represents the collision's status, the RTS/CTS transmissions' status, and the multiple DATA/ACK transmissions' status. Thus, if collision-free, the chain will go to $(i, -1)$ (as shown by the arrow with a mark of (a)), and then if RTS error-free, it will go to $(i, -2)$, and so on. Finally, if collision-free and error-free for all the frames involved (RTS/CTS/DATA/ACK), the burst is successfully trans-

[1]The same assumption is also adopted in [3].

mitted, which leads the chain to the first back-off stage as indicated by the arrow with a mark of (c). On the contrary, if there is any error occurred, the burst is terminated and the back-off procedure is restarted, which leads the chain to the next back-off stage as indicated by the arrow with a mark of (b)

Given this model, however, in what follows we will instead use a simplified model to obtain the transmission probability $\tau$, and with this probability, we can then obtain the maximum achievable throughput by means of the complete Markov chain model shown in Fig. 2. For the first step, a simplified Markov chain is made here by merging the states in the upper half for each stage $i$ and the state $(i, 0)$ in the bottom half as a virtual state $(i', 0')$, and renaming the other states $(i, j)$s by $(i', j')$s. With the simplified and equivalent model, we let $b(t)$ and $s(t)$ denote the stochastic processes representing the back-off timer and the back-off stage, respectively, for a given station at slot time $t$. Then, the non-null probabilities involved can be represented by

$$\begin{cases} P\{i', k'|i', (k+1)'\} &= 1, \\ & \text{if } k' \in (0', (W_i-2)'), \\ & \text{and } i' \in (0', m') \\ P\{0', k'|i', 0'\} &= \frac{1-\widetilde{P}}{W_0}, \\ & \text{if } k \in (0', (W_0-1)'), \\ & \text{and } i' \in (0', m') \\ P\{i', k'|(i-1)', 0'\} &= \frac{\widetilde{P}}{W_i}, \\ & \text{if } k' \in (0', (W_i-1)'), \\ & \text{and } i' \in (1', m') \\ P\{0', k'|m', 0'\} &= \frac{1}{W_0}, \\ & \text{if } k' \in (0', (W_m-1)') \end{cases} \tag{1}$$

where $\widetilde{P} = 1 - P_T$, and $P_T$ denotes the probability leading the current state to the first back-off stage. Clearly, the latter ($P_T$) involves the probability of collision-free, that of RTS/CTS transmission successful, and that of multiple DATA/ACK transmission successful. That is,

$$\begin{aligned} P_T &= (1-P_c)\cdot(1-P^f_{rts})\cdot(1-P^f_{cts})\cdot \\ &\quad \Big((1-P^f_{data})\cdot(1-P^f_{ack})\Big)^{N_b} \end{aligned} \tag{2}$$

where $P_c$ denotes the conditional probability of collision, and can be calculated by $1-(1-\tau)^{N-1}$ given $N$ completing stations in the network. $N_b$ is the maximum number frames transmitted in a TXOP limit. $P^f_{rts}$, $P^f_{cts}$, $P^f_{data}$, and $P^f_{ack}$ represent the frame error probabilities of RTS/CTS/DATA/ACK frames, respectively, and can be obtained by $1-(1-P_b)^l$, with bit error rate of $P_b$ and frame size of $l$ bits.

With the above, and after some algebra manipulations similar to that in [2], we can obtain the stationary probability of state $(0', 0')$ as

$$b_{0',0'} = \frac{\alpha}{\beta} \tag{3}$$

where

$$\begin{aligned} \alpha &= 2(1-2\widetilde{P})(1-\widetilde{P}) \\ \beta &= \begin{cases} W_0(1-(2\widetilde{P})^{m+1})(1-\widetilde{P}) + \\ (1-2\widetilde{P})(1-\widetilde{P}^{m+1}), \\ \text{if } m \le m' \\ \\ W_0(1-(2\widetilde{P})^{m'+1})(1-\widetilde{P}) + \\ (1-2\widetilde{P})(1-\widetilde{P}^{m+1}) + \\ W_0 2^{m'}\widetilde{P}^{m'+1}(1-2\widetilde{P})(1-\widetilde{P}^{m-m'}), \\ \text{if } m > m' \end{cases} \end{aligned}$$

In above, $m'$ represents the largest contention window size. Finally, we can attain the probability $\tau$ that a station transmits a frame in a randomly chosen slot time by

$$\begin{aligned} \tau = \sum_{i'=0}^{m} b_{i',0'} &= \sum_{i'=0}^{m} \widetilde{P}^{m+1}\cdot b_{0',0'} \\ &= \frac{1-\widetilde{P}^{m+1}}{1-\widetilde{P}}\cdot b_{0',0'} \end{aligned} \tag{4}$$

Now, it can be seen that the relationship between $\widetilde{P}$ and $\tau$ in fact represents a non-linear system involving the parameters $W_0$, $m$ , $m'$, $N$, $N_b$, and $P_b$. That is, $\tau = f(W_0, m, m', N, N_b, P_b)$, which can be solved with numerical methods.

## 3.2 Throughput Calculation

In this work, we consider the NA method with the IEEE 802.11a PHY, which provides different modulation schemes with corresponding different data rates (namely, 6, 9, 12, 18, 24, 36, 48, and 54 Mbps). According to the standard, data frame and control frame are transmitted with different rates. Thus, we denote the rate for data frame by $r$ and that for control frame by $r^*$. Specifically, a control frame is transmitted with the lowest rate (6 Mbps) in order to reach the most distant station in the 802.11a WLAN for robustly preventing collisions in the network, as mentioned previously. The channel occupancy time of RTS/CTS exchange, data frame and ACK, are denoted by $RTS$, $CTS$, $DATA$, and $ACK$, respectively. In above, a data frame with payload size of $L$ should also include a MAC header. As a reference, all the times involved are summarized in Table 1, which also includes that for the BA method. However, it does not show the details such as that each frame should include a common physical header, and its transmission time has to

Table 1: PHY payload and header transmission times

| RTS | CTS | ACK | BREQ | BACK | DATA |
|---|---|---|---|---|---|
| $160/r^*$ | $112/r^*$ | $112/r^*$ | $192/r$ | $1216/r$ | $(MAC+P)/r$ |

Table 2: Channel Occupancy Times

| | $T_A^O$ | $T_R^O$ | $T^P$ |
|---|---|---|---|
| NA | $RTS+2\cdot SIFS+CTS$ | 0 | $DATA+2\cdot SIFS+ACK$ |
| BA | $RTS+2\cdot SIFS+CTS$ | $BREQ+2\cdot SIFS+BACK$ | $DATA+SIFS$ |

be added to the PHY payload time, although our simulations involve all the details.

For the throughput calculation, we consider that any block does not split among multiple TXOPs, and hence a data block corresponds to a single data burst. In addition, we consider also that the channel occupancy time is divided into three components. That is, 1) the overhead for channel access, $T_A^O$, 2) the time for data payload transmission, $T^P$, and 3) the overhead for channel release, $T_R^O$. Specifically, a burst transmission is composed of a given number of unit times of $T^P$ because the latter only corresponds to the time for the transmission of a single data frame. Note that in these time components, $SIFS$ denotes the short interframe space in the IEEE 802.11 standard. For reference, we summarize the values of these components in Table 2, including also that for the BA method. Given that, we can now focus on the saturated throughput of the network represented by the data payload transmitted in a slot time divided by the average length of a slot time. That is,

$$S=\frac{E[m]}{E[T]} \tag{5}$$

where

$$\begin{aligned} E[m] &= P_s\cdot P_{tr}\cdot E[N_s]\cdot E[L] \\ E[T] &= (1-P_{tr})\cdot\sigma+P_{tr}\cdot P_s\cdot P_{succ}\cdot T_s + \\ & \quad P_{tr}\cdot(1-P_s)\cdot T_c+P_{tr}\cdot P_s\cdot E[T_e] \end{aligned}$$

In (5), $E[L]$ is the average data payload size, and we assume that all frames have the same size, i.e., $E[L]=L$. $E[N_s]$ is the average number of frames successfully transmitted in a burst transmission. $P_{tr}$ is the probability that at least one station transmits in a time slot, and can be obtained by $P_{tr}=1-(1-\tau)^N$. Thus, the probability of an empty slot can be derived by $1-P_{tr}$, which consumes an empty slot time $\sigma$. $P_s$ is the probability of a single successful transmission given at least one station is transmitting, i.e., $P_s=(N\cdot\tau\cdot(1-\tau)^{N-1})/P_{tr}$. Based on the above, we note that 1) the probability that all data frames in a burst are transmitted successfully is given by $P_{tr}\cdot P_s\cdot P_{succ}$, and 2) the unsuccessful transmission probability due to collisions is $P_{tr}\cdot(1-P_s)$. The two probabilities are accounted for the corresponding times, i.e., the average time the channel sensed busy due to a successful transmission or a collision, $T_s$, and $T_c$, respectively. And these times can be obtained by

$$\begin{aligned} T_s &= T_A^O+N_b\cdot T^P+T_A^R-SIFS+DIFS \\ T_c &= RTS+DIFS \end{aligned} \tag{6}$$

where $DIFS$ denotes the distributed interframe space in the IEEE 802.11 standard. In addition to that, with the new operations of EDCA, we should also take into account the average time the channel being sensed busy due to successful RTS/CTS exchange but incomplete multiple data frame transmissions in a burst. This is represented by $P_{tr}\cdot P_s\cdot E[T_e]$.

Now, we refer to the complete Markov chain model in Fig. 2 in order to derive the parameters involved in above but not yet solved. At first, the maximum number frames transmitted in a TXOP limit is obtained by

$$N_b=\lfloor\frac{TXOP-T_A^O-T_R^O+SIFS}{T^P}\rfloor \tag{7}$$

Here, a SIFS is involved due to its overlap between $T_A^O$ and $T^P$. Given this number, we can consider that a burst may be terminated on the $i+1$th data frame due to its frame error or the corresponding ACK's error. In this case, there are only the first $i$ frames successfully transmitted. Thus, $E[N_s]$ can be represented by

$$\begin{aligned} E[N_s] &= \left(\sum_{i=2}^{N_b}(i-1)\cdot(P_f^{data}(i)+P_f^{ack}(i))\right)+ \\ & \quad P_{succ}\cdot N_b \end{aligned} \tag{8}$$

In above, the probability that a burst is terminated on the $i$th data frame includes the successful probability of RTS/CTS exchange, that of the first $i-1$ data/ACK transmissions, and the failure probability of the $i$th data frame. That is,

$$P_f^{data}(i) = (1-P_{rts}^f)\cdot(1-P_{cts}^f)\cdot(1-P_{data}^f)^{i-1}\cdot (1-P_{ack}^f)^{i-1}\cdot P_{data}^f \quad (9)$$

Similarly, the probability that a burst is terminated on the $i$th ACK can be obtained by

$$P_f^{ack}(i) = (1-P_{rts}^f)\cdot(1-P_{cts}^f)\cdot(1-P_{data}^f)^{i}\cdot (1-P_{ack}^f)^{i-1}\cdot P_{ack}^f \quad (10)$$

On the contrary, if all data/ACK frames in a burst are successfully transmitted, the probability should be

$$P_{succ} = (1-P_{rts}^f)\cdot(1-P_{cts}^f)\cdot \Big((1-P_{data}^f)\cdot(1-P_{ack}^f)\Big)^{N_b} \quad (11)$$

Given these probabilities, we can now consider the corresponding times for the different cases. First, the average time spent for an incomplete burst transmission is obtained by finding the expectation of the times required by transmission failures occurred at different points of time. That is, a burst may fail on RTS/CTS exchange or the $i$th data/ACK transmission. Taking these into account, we can obtain the average time by

$$E[T_e] = P_{rts}^f\cdot T_{rts}^f + (1-P_{rts}^f)\cdot P_{cts}^f\cdot T_{cts}^f + \sum_{i=1}^{N_b} P_f^{data}(i)\cdot T_f^{data}(i) + P_f^{ack}(i)\cdot T_f^{ack}(i) \quad (12)$$

Here, a failure on RTS/CTS exchange will spend a period of time that ensures the corresponding CTS failure, and a period of timeout before the BEB procedure can be restarted. That is,

$$T_{rts}^f = T_{cts}^f = T_A^O - SIFS + T_{timeout} \quad (13)$$

The last term in above, $T_{timeout}$, is obtained by

$$T_{timeout} = EIFS - DIFS + AIFSN[AC]\cdot\sigma + SIFS - T_{TurnaroundTime} \quad (14)$$

according to [1]. For the timeout, we let $AIFSN[AC] = 2$ because it is the minimal setting allowed for an EDCA station, and we ignore $T_{TurnaroundTime}$ when it is small as compared with the other components. Similarly, $T_f^{data}(i)$ and $T_f^{ack}(i)$ can be considered by taking into account the time required by the first $i$ data/ACK transmissions and then $T_{timeout}$. That is,

$$T_f^{data}(i) = T_f^{ack}(i) = T_A^O + i\cdot T^P - SIFS + T_{timeout} \quad (15)$$

# 4 Throughput Analysis of The BA Method

In this section, we analyze the BA method for its throughput performance. To this end, we consider its Markov chain model first. As shown in Fig. 3, only the upper half of this model is drawn here for the bottom half has been given in Fig. 2. In this model, the upper half similarly represents the states after reaching the zero back-off count at stage $i$. However, unlike the NA method, only four states are involved here. That is, collision-free leads the chain to $(i,-1)$ , and then RTS/CTS error-free leads to $(i,-2)$ and $(i,-3)$, respectively. The first three states are the same as those of the NA method. However, in the BA method, the multiple data frames in a burst transmission require no responses (ACKs). Thus, only BREQ and BACK should be considered with their frame errors. Hence, if RTS/CTS exchange is successful and BREQ is error-free, the chain will go to $(i,-4)$. Finally, if BACK is also error-free, the burst is considered to be successfully transmitted, leading the chain to a state in the first back-off stage. Otherwise, the chain moves to the next back-off stage.

With a similar simplified Markov chain model as that for the NA method, we can obtain the transmission probability $\tau$ for the BA method. Given this probability, we can obtain the method's maximum achievable throughput with the same equation of (5). Of course, some parameters involved should be modified to accommodate themselves to this method. The first to be considered is that, instead of using a single ACK to response a data frame, in the BA method all data frames in a burst transmission is acknowledged with only one BACK. It implies that the RTS/CTS exchange and the BREQ/BACK exchange should be all successful. Otherwise, the sender can not confirm which frame is correctly received even though its multiple back-to-back data frames are all transmitted in a burst. Thus, $P_T$ in (2), which denotes the probability leading the current state to the first back-off stage, should be replaced by

$$P_T = (1-P_c)\cdot(1-P_{rts}^f)\cdot(1-P_{cts}^f)\cdot (1-P_{breq}^f)\cdot(1-P_{back}^f) \quad (16)$$

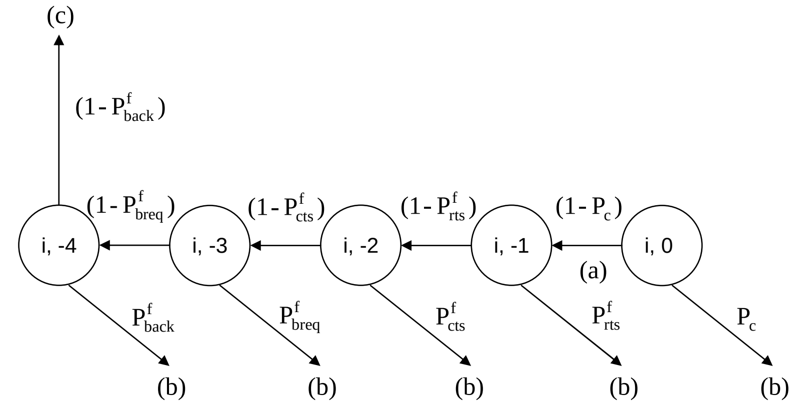



Figure 3: Markov chain model for the BA method.

where $P^f_{breq}$ and $P^f_{back}$ denote the frame error probabilities of BREQ/BACK frames, respectively, and similar to those for the other frames, they can be also obtained by $1-(1-P_b)^l$ with bit error rate of $P_b$ and frame size of $l$ bits. Similarly, for the BA method, the successful probability in the denominator part of (5) should be rewritten as

$$P_{succ} = (1-P^f_{rts})\cdot(1-P^f_{cts})\cdot(1-P^f_{breq})\cdot(1-P^f_{back}) \tag{17}$$

With this probability, a station can know which and how many frames are successfully transmitted in a burst when the corresponding BACK is correctly received. In addition, although a transmission burst consists of $N_b$ frames, there may have only $i$ frames located in different positions in the burst to be acknowledged. Taking these into account, we have $E[N_s]$ for the BA method as

$$E[N_s] = P_{succ}\cdot\sum_{i=0}^{N_b} i\cdot\left(\begin{array}{c} N_b \\ i \end{array}\right)(1-P^f_{data})^i\cdot(P^f_{data})^{N_b-i} \tag{18}$$

Similarly, a station can know its failures on transmitting RTS, CTS, BREQ, and BACK frames, despite the unknown status of its multiple data transmissions that can only be solved with a BACK. Therefore, we can consider the average time spent on the failure as

$$\begin{aligned} E[T_e] \quad = \quad & P^f_{rts}\cdot T^f_{rts} + (1-P^f_{rts})\cdot P^f_{cts}\cdot T^f_{cts} + \\ & (1-P^f_{rts})\cdot(1-P^f_{cts})\cdot P^f_{breq}\cdot T^{breq}_f + \\ & (1-P^f_{rts})\cdot(1-P^f_{cts})\cdot(1-P^f_{breq})\cdot \\ & P^f_{back}\cdot T^{back}_f \end{aligned} \tag{19}$$

In above, the time for BREQ or BACK failure consists of the whole period of time for a burst transmission because a station should wait a period of time to confirm the BACK failure, and then wait a $T_{timeout}$ period to restart the BEB procedure. Thus, we have

$$T^{breq}_f = T^{back}_f = T^O_A + N_b\cdot T^P + T^O_R - SIFS + T_{timeout} \tag{20}$$

# 5 Performance Evaluation

In this section, we report on experiments made in order to verify the performance results derived previously. To this end, we design our experiments to focus on the new methods in EDCA and ignore the other characteristics in the MAC. That is, we consider that each station carries a single traffic flow with the same access category (AC) that provides only one set of parameters for each station. For example, we let $r^*$ be 6 Mbps, $m'$ be 5, $m$ be 7, $CW_{min}$ (the minimum contention window size) be 31, $CW_{max}$ (the maximum contention window size) be 1023, and $L$ (the frame size) be 1024, for each station.

Specifically, we conduct four different sets of experiments to exhibit the different effects resulted from the four major factors to be considered, which are bit error probability ($P_b$), TXOP limit, number of stations, and data transmission rate. To focus on the effects of a single factor, the four sets of experiments are so conducted to vary one of these factors while remaining the others fixed, as summarized in Table 3. For example, in the first set, we let the data rate be 54 Mbps, the number of stations be 100, and the TXOP limit be 10 ms and 100 ms, respectively, while varying the bit error probability under consideration from $P_b = 0$ to $P_b = 10^{-3}$. Given that, for each set we consider the normalized throughput, defined as the throughput divided by the data transmission rate adopted. The corresponding results are given in Fig. 4. The first set's

Table 3: Experiments in the Performance Evaluation

| Tag | bit error probability ($P_b$) | TXOP limit (ms) | number of station | data transmission rate (Mbps) |
|---|---|---|---|---|
| a | 0 to $10^{-3}$ | 10 and 100 | 100 | 54 |
| b | 0 and $10^{-5}$ | 2 to 100 | 100 | 54 |
| c | 0 and $10^{-5}$ | 10 | 10 to 100 | 54 |
| d | 0 and $10^{-5}$ | 10 | 100 | 6 to 54 |

results are given in Fig. 4 (a), and the other results are given in the subfigures (b), (c), and (d), respectively.

As shown in Fig. 4 (a), the throughput decreases when $P_b$ increases, as expected. Another expected result is that the higher TXOP limit (100 ms) provides higher throughput than that of the lower one (10 ms). However, it should be noted that although the higher limit is 10 times of the lower limit (100 ms/10 ms=10), its improvement on the throughput is much lower than the scale (10 times). This is also expected because the existed overheads in the MAC, e.g., the time required by the common physical header and the necessary spacing time such as SIFS, will inevitably consume the bandwidth. In addition, we also observe that the BA method provides higher throughput than that of the NA method. This is because the former eliminates the ACK overhead for each data frame in a transmission burst. However, when $P_b$ is high (e.g., $10^{-3}$), the multiple frames spaced with only SIFS in a burst will not be correctly received with a high probability, and the BA method can only provide nearly the same throughput as the NA method.

In Fig. 4 (b), we show more the throughput results that correspond to not only the TXOP limit of 10 ms and 100 ms but also that from 2 ms to 100 ms, while fixing $P_b$ at 0 and $10^{-5}$, respectively. From this figure, it can be seen that the curves for the two new methods (NA and BA) increase more steeply when the TXOP limit increases at the beginning from 2 to 10 ms as compared with that after 10 ms. On the contrary, the IEEE 802.11 MAC remains the same flat curves because no TXOP limit is given in the MAC and only $P_b$ can affect its results. From this figure as well as Fig. 4 (a), we can clearly observe the marginal benefit to be obtained with the new methods when the TXOP limit increases, and its trend would persist despite $P_b$.

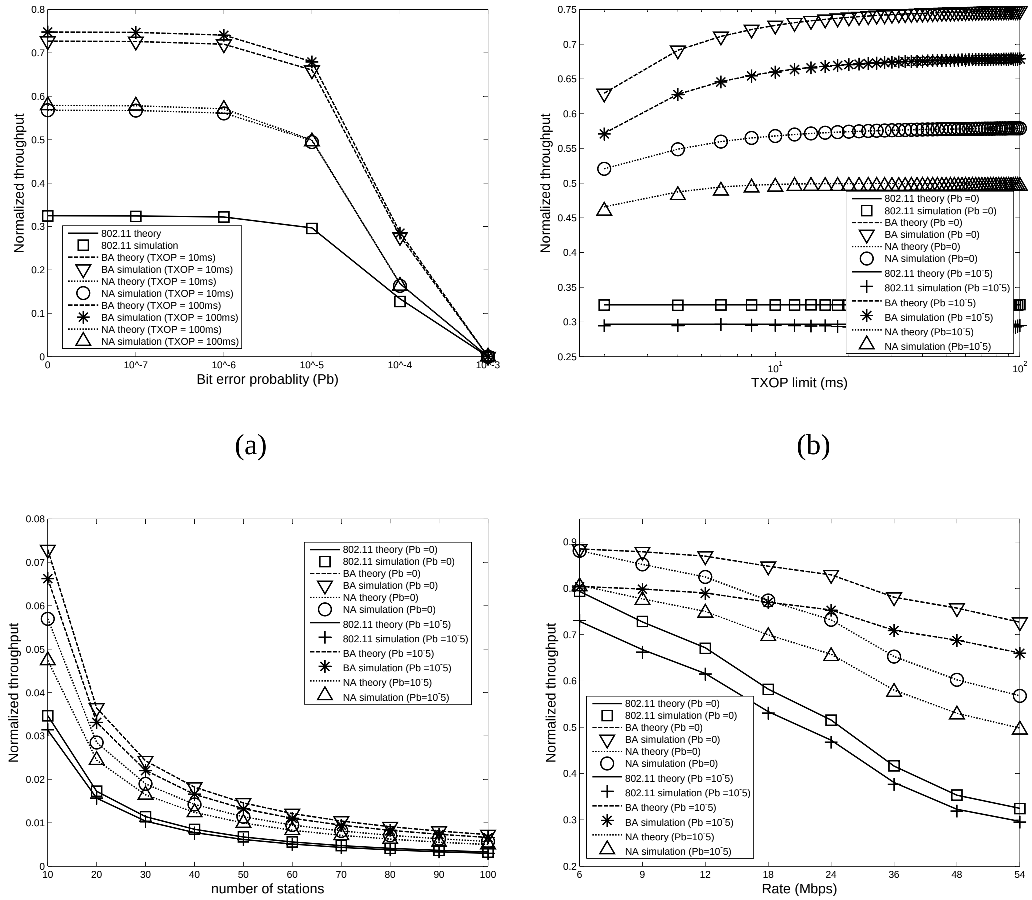
In Fig. 4 (c), we show the throughput results for each station in the network. As shown in this figure, the per-station throughput decreases as the number of stations increases. This is expected because the increase of the number of stations will increase the channel contention level, which eventually decreases the throughput. Finally, in Fig. 4 (d), it can be observed that the normalized throughput decreases as the data rate increases. It's no surprise because even though the data rate could continuously increase, the control overhead can not be avoided and still remain constant. This overhead will occupy more bandwidths and thus reduce more throughputs as the data rate increases.

## 6 Related Works

In the decade, many related works for WLANs, e.g., [2, 4–8], have been done for the legacy IEEE 802.11 MAC. Most of them complete their analyses with the assumptions that 1) the network is saturated (i.e., every station always has a packet waiting to be transmitted), and 2) transmission error is a result of frame collision and is not caused by medium error. Although these assumptions provide a tractable basis for the analyses and give these related works remarkable accuracy in theory, such assumptions may not be valid in the real world.

As a follower of the legacy MAC, IEEE 802.11e uses the TXOP mechanism to increase system throughput. With the same aim, there are also some other works proposed to provide better throughput when the channel condition is good for multiple frames to be transmitted in a burst [3, 9–13]. These protocols have their own specifications and mechanisms, and thus, do not provide exactly the same two operations of IEEE 802.11e. Therefore, the results for those protocols can not be directly applied to the operations under consideration.

Apart from the above, only a few results have been reported about the new operations under consideration. Currently, only theoretical maximum throughput, theoretical throughput upper limit, and/or theoretical delay lower limit have been proposed in literature [14–17]. None of the above involves a fading channel. On the other hand, although some efforts had been done for the performance analysis under a fading channel, e,g., [18–21], these efforts mainly focus on the legacy IEEE 802.11 MAC and involve no the operations under consideration.




(a) (b)

(c) (d)

Figure 4: Analysis and simulation results of throughput for the four major factors under consideration: (a) the $P_b$ results with TXOP limit = 10 ms and 100 ms, (b) the TXOP limit results with $P_b = 0$ and $10^{-5}$, (c) the results from different numbers of stations with $P_b = 0$ and $10^{-5}$ and (d) the results from different numbers of rates with $P_b = 0$ and $10^{-5}$.

# 7 Conclusion

In this paper, we derive the maximum achievable throughput for the new methods of EDCA (NA and BA) in an error-prone WLAN with a modified Markov chain model that can take into account the channel error. Our experiments confirm the correctness of our derivation, and show their results to be very consistent with those of the theory. From both the theory and the experiments, we can see that the two methods outperform the IEEE 802.11 MAC from the four aspects under consideration: bit error probability, TXOP limit, number of stations, and data transmission rate. In addition, we also find that the BA method usually outperforms the NA method because the former requires only a BACK for a bulk of data transmissions and thus reduces the transmission overhead under most of the fading conditions. As a summary, it could be concluded that with the especial concern on the behavior of these methods under the error-prone channel, the performance model can provide more insights on the design criteria for the IEEE 802.11-based WLANs operated in the real world, beyond that for the networks under an ideal error-free environment.

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*References:*

[1] IEEE 802.11 e. Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 8: Medium

Access Control (MAC) Quality of Service Enhancement. November 2005.

[2] G. Bianchi. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. *IEEE Journal on Selected Areas in Communications*, 18(3):535–547, March 2003.

[3] Jain-Shing Liu and Chun-Hung Richard Lin. ECTP: An Energy-Efficiency Label-Switching MAC Protocol for Infrastructure Wireless Networks. *IEEE Transactions on Vehicular Technology*, 56(3):1399–1417, May 2007.

[4] H.S. Chhaya and S. Gupta. Performance Modeling of Asynchronous Data Transfer Methods in the IEEE 802.11 MAC Protocol. *ACM/Balzer Wireless Networks*, 3:217–234, 1997.

[5] Omesh Tickoo and Biplab Sikdar. Queueing Analysis and Delay Mitigation in IEEE 802.11 Random Access MAC based Wireless Networks. *in Proceedings of INFOCOM'04*, 2:1404–1413, March 2004.

[6] Jain-Shing Liu. Uplink and Downlink Resource Allocation in IEEE 802.11 DCF-Based WLANs. *WSEAS Transactions on Communications*, 5:603–610, April 2006.

[7] Shun-Ping Chung and Wei-Sin Chen. Analysis of Prioritized IEEE 802.11 Wireless LAN with Non-Saturated Traffic. *WSEAS Transactions on Communications*, 5:1725–1732, Sept. 2006.

[8] Bai Xiang and Mao Yu-Ming. A Simple Adaptive p-persistent MAC Scheme for Service Differentiation and Maximum Channel Utilization. *WSEAS Transactions on Communications*, 7:1–7, Jan. 2007.

[9] IrDA: Advanced Infrared (AIr) MAC draft protocol specification - version 1.0. (Infrared Data Association, 1999).

[10] B. Sadeghi and V. Kanodia and A. Sabharwal and E. Knightly. Opportunistic Media Access for Multirate Ad Hoc Networks. *Proceedings of MobiCom 2002*, 2002.

[11] G. Holland, N. Vaidya, and P. Bahl. A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks. *in Proceedings of ACM MOBICOM'01*, 2001.

[12] C. R. Lin, and Y. J. Chang. AAR: An Adaptive Rate Control Protocol for Mobile Ad Hoc Networks. *in Proceedings of ICON 2003*, 2003.

[13] K. Lu, D. Wu, Y. Fang, and R. Qiu. Performance Analysis of A Burst-Frame-Based MAC Protocol for Ultra-Wideband Ad Hoc Networks. *in Proceedings of IEEE International Conference on Communications (ICC 2005)*, May 2005.

[14] Yang Xiao and Jon Rosdahl. Performance Analysis and Enhancement for the Current and Future IEEE 802.11 MAC Protocols. *Mobile Computing and Communication Review*, 7(2), April 2003.

[15] E. Varthis, P. Theodorou. and A.C. Boucouvals. Analysis of Burst Acknowledgment Mechanism of IEEE 802.11e MAC Protocol over Infrared Wireless LANs. *in Proceedings of IEEE International Conference on Software, Telecommunications and Computer Networks (SoftCom)*, October 2003.

[16] V. Vitsas and A.C. Boucouvalas. Performance Analysis of the Advanced Infrared (Air) CSMA/CA MAC Protocol for Wireless LANs. *Wireless Networks*, 9:495–507, 2003.

[17] Ilenia Tinnirello and Sunghyun Choi. Efficiency analysis of burst transmissions with block ACK in contention-based 802.11e WLANs. *in Proceedings of IEEE International Conference on Communications (ICC)*, 5:3455–3460, May 2005.

[18] Pero Latkoski, Zoran Hadzi-Velkov and Borislav Popovski. Performance analysis of IEEE 802.11a WLAN in block fading channel using SDL simulation. *in Proceedings of IEEE TELSIKS 2005*, 1:97–100, Sept. 2005.

[19] Xiaohui Xu and Xiaokang Lin. Throughput Enhancement of the IEEE 802.11 DCF in fading channel. *in Proceedings of IEEE International Conference on Wireless and Optical Communications Networks*, pages 1–5, April 2006.

[20] Periklis Chatzimisios, Anthony C. Boucouvalas and Vasileos Vitsas. Performance Analysis of IEEE 802.11 DCF in Presence of Transmission Errors. *in Proceedings of IEEE International Conference on Communications*, 7:3854 – 3858, June 2004.

[21] Jun Yin, Xiaodong Wang and Dharma P. Agrawal. Optimal Packet Size in Error-prone Channel for IEEE 802.11 Distributed Coordination Function. *in Proceedings of IEEE International Conference on Wireless Communications and Networking Conference (WCNC)*, 3:1654–1659, March 2004.