Performance Analysis of the IEEE 802.11n Block-ACK Mechanism in an Error-Prone Channel

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Abstract. A Block-ACK mechanism is adopted to improve the performance of WLAN in IEEE 802.11n, through Block-ACK mechanism stations can transmit more MPDUs at one-time and receiver only responds to a single Block-ACK frame, thus the mechanism effectively improves the efficiency of the MAC layer. In this paper, we analyze the saturation throughput of Block-ACK mechanism by considering the freezing of backoff counter, anomalous slots and non-ideal channel, the accuracy of our model is verified by the NS-2 simulation results.

Introduction

With the WLAN appearing on many emerging applications and services, the demands for the IEEE 802.11 are higher and higher, particularly in terms of speed. In order to meet the demands, IEEE 802.11n [1] in October 2009 became the official standard. The rate in which can reach 600 Mbps due to MIMO and OFDM technology be adopted in the physical layer. However, that is not well improve the throughput of system because of the high MAC overhead. In order to reduce the MAC overhead, IEEE 802.11n introduces the Block-ACK mechanism that is enhanced from the IEEE 802.11e standard [2] to improve the throughput of MAC layer significantly by shrinking the ACK frames.

Many articles have analyzed frame aggregation mechanism and Block-ACK mechanism. Wang C Y [3], Kloap J [4] and Selvam T [5] gave the detailed description of IEEE 802.11n protocol and simulation results, but they did not propose an analytical model. Daldoul Y [6] proposed an analytical model to calculate the impact of the frame aggregation of the multicast traffic, however they did not consider the backoff overhead. Liu [7] proposed a mathematical model of Block-ACK mechanism in an ideal channel, although Li T [8], Chen Y [9] and Lee [10] proposed an analytical model in a noisy channel, but they did not consider the anomalous slots, the freezing of backoff counter and these models were based on IEEE 802.11e protocol. Chen H [11] proposed a Markov model by considering anomalous slots, but the result about saturation throughput was inaccurate, and he ignored the error probability of the BAR frame and the BA frame. These articles [7-10] have enhanced the two-dimensional Markov model which was proposed by Bianchi G [12] by considering a Block-ACK case. But they have ignored some details in the IEEE 802.11 protocol, such as the freezing of backoff counter and anomalous slots. Tinnirello [13] gave a detailed explanation about those anomalous slots. Here we briefly introduce anomalous slots: backoff counter start to decrease only under the idle slots, when a STA successful transmission and the backoff value equals to zero the STA occupies the channel again. In [13] a more accurate model was proposed to consider the freezing of backoff counter and the anomalous slots in an ideal channel. For research performance of the Block-ACK, it is necessary to consider bit error rate of the channel. Chen H [14] proposed an analytical model in an erroneous channel, but it is the study of immediate ACK mechanism not Block-ACK mechanism.

In this paper, we combine the mathematical model in [14] with Block-ACK mechanism and take into account the anomalous slots. We derive the saturation throughput formula of Block-ACK by the model and use NS-2 verify the accuracy of the model. The following contents are arranged as follows: the second part introduces Block-ACK mechanism in details, the third part gives the model
and analyze saturation throughput, the fourth part gives the simulation results and the fifth part summarize the article.

The Block-ACK of 802.11n

Block-ACK mechanism has been used in the IEEE 802.11e firstly and expanded in the IEEE 802.11n that put forward the compressed Block-ACK mechanism and immediate Block-ACK mechanism. When sender and receiver want to use the Block-ACK mechanism, sender sends an add Block-ACK request frame (add BA-REQ) to the receiver, receiver which support Block-ACK mechanism will responds to an add Block-ACK response frame (add BA-RSP), so they can use Block-ACK mechanism for data transmission.

Channel access procedure of Block-ACK mechanism as shown in Figure 1. After the initialization, the sender sends a MPDU to contend channel, the STA can sends a data block that is composed of multiple MPDUs and each MPDU between SIFS interval once it receives the ACK frame correctly. When STA finishes the data block transmission, it sends a Block-ACK request frame (BAR) that tell the receiver data block are sent over to request the BA frame. Receiver responds a Block-ACK frame (BA) to the sender once it receives one of MPDUs of the data block or the BAR frame correctly. BA frame is an aggregated frame that use bitmap to store confirm information of these MPDUs. Due to a BA frame can confirm the maximum number of MPDUs which is 64, so a data block can not more than 64 MPDUs.

Figure 1  illustrates multiple MPDUs, BAR frame and BA frame are all in the same backoff procedure and only a BA frame be used to acknowledge the data block. So Block-ACK mechanism greatly reduces the MAC layer overhead.

In this article, we discuss the Block-ACK mechanism with a basic access channel mechanism in a noisy channel. In the case of collision, at least two STAs start transmission in a slot, each of them sends out the first MPDU and then waits for the ACK frame, the senders can’t receive the ACK frame because collisions, so the senders have to retry their data again. In the incorrect case, only one STA start transmission, here we assume that BAR frame, ACK frame and BA frame have the error probability. The sender sends the first MPDU but it can’t receive the ACK frame due to the MPDU or ACK frame transmits error, then the contention window is doubled and retry its data. If the STA successful receives the ACK frame indicates it wins the channel and can transmits the data block. The STA can’t receive the BA frame due to the data block and the BAR frame all errors or the BA frame error, then the contention window is doubled too and retry its data. Once the receiver receive one of MPDUs of the data block or the BAR frame correctly, it will responds the BA frame in a SIFS interval. Once receiving the BA frame correctly, the sender should waits a DIFS interval and starts a new backoff procedure. Taking into account anomalous slots, when the next backoff value equals to zero the STA occupies the channel again. Meanwhile, all the other STAs should be frozen their backoff counter with a DIFS interval and when the channel is idle they begin to decrease their backoff counter.

So it can be seen that the Block-ACK mechanism operates in a similar way to the [14]. So it is possible to extend the analysis [14] to study the Block-ACK mechanism.
Analytical Model of Block-ACK

Chen H [14] has proposed a two-dimensional Markov chain \((s(t), b(t))\) to model the immediate ACK mechanism backoff behavior of considering anomalous slots and the freezing of backoff counter in a noisy channel. So it is very suitable for Block-ACK mechanism, but the probability of a STA double the contention window need to be computed again due to the BAR frame and the BA frame can suffer errors too. The model is based on the discrete time and the wireless channel model is divided into a series of slot times. The definition of model slot as shown in Figure 2.

![Figure 2. The definition of model slot time. [12]](image)

The Markov Chain

In this paper, the Markov chain model is extended from [14], the model considers the wireless channel is a Gaussian channel, in which each packet has the same bit error probability (BER), let \(p_{\text{ber}}\) represents the BER and each STA is always ready to send MPDU. Let \(p_E\) denotes the probability of the each MPDU transmits error. We assume each MPDU has the same size \(S_{\text{data}}\), and each STA sends \(L_{\text{BA}}\) MPDUs, so the data block is composed of \(L_{\text{BA}}-1\) MPDUs. \(p_{e}\) represents the probability of one STA double its contention window, may be collision or errors. \(\tau\) stands for the probability that a STA transmits in a randomly chosen slot time. \(p_{c}\) represents the probability of collision, \(N\) is the number of contend STAs. \(p_{e}\) represents the probability that the STA double its contention window because of transmission errors, let \(S_{\text{ACK}}, S_{\text{BAR}}, S_{\text{BA}}, p_{\text{BA}}, p_{\text{ACK}}, p_{\text{ALL}}\) represent the size of the ACK frame, the size of the BAR frame, the size of the BA frame, the probability of the BAR error, the probability of the BA error, the probability of the ACK error, the probability of these MPDUs of the data block all errors, respectively. So:

\[
\begin{align*}
    p_E &= 1 - (1 - p_{\text{ber}})^{S_{\text{data}}} \\
    p_{\text{ALL}} &= p_E^{L_{\text{BA}} - 1} \\
    p_{\text{BAR}} &= 1 - (1 - p_{\text{ber}})^{S_{\text{BAR}}} \\
    p_{\text{BA}} &= 1 - (1 - p_{\text{ber}})^{S_{\text{BA}}} \\
    p_{\text{ACK}} &= 1 - (1 - p_{\text{ber}})^{S_{\text{ACK}}} \\
\end{align*}
\]

The probability \(p_{e}\) is related to the transmission situation of the MPDU, the ACK, the data block, the BAR, the BA. So these probabilities \(p_{c}, p_{f}\) and \(p_{e}\) can be expressed as follows:

\[
\begin{align*}
    p_c &= 1 - (1 - \tau)^{N-1} \\
    p_{c} &= p_E + (1 - p_E)p_{\text{ACK}} + (1 - p_E) \cdot (1 - p_E) \cdot (1 - p_{\text{ACK}}) \cdot (p_{\text{ALL}} \cdot p_{\text{BAR}} \cdot p_{\text{BA}} - p_{\text{ALL}} \cdot p_{\text{BAR}} \cdot p_{\text{BA}}) \\
    p_f &= p_e + p_c - p_c \cdot p_e \\
\end{align*}
\]

In this model after errors occur the contention window is doubled and \(R\) is the number of maximum retransmission. According to the regular of the Markov chain, the probability \(\tau\) can be solved, [14] has the detailed derivation for the model. Define \(\Psi = p_{c}/(W + p_{c}-1)\), where \(W = CW_{\text{min}} + 1\), \(W_k = CW_k + 1\), \(CW_k\) denotes the contention window in the \(k\)th retry, \(CW_{\text{min}}\) is the minimum contention window, the final result is derived as follows:
\[
\tau = \frac{2(1 - p_{f+1}^i)}{(1 - p_f^i) \left( \sum_{k=1}^{\infty} (W_k + 1) \left[ \Psi^* \cdot p_{f+1}^k + (1 - \Psi) p_f^k \right] + W + 1 - (1 - \Psi) (1 - p_{f+1}^i) \right)}
\]  

(3)

Saturation Throughput

Before analyzing the saturation throughput we define some parameters. Let \( \sigma, T_{\text{MPDU}}, T_{\text{ACK}}, T_{\text{BAR}}, T_{\text{ACKTIMEOUT}}, T_{\text{DIFS}}, T_{\text{SIFS}}, T_{\text{EIFS}} \) denote the duration of an idle slot time, the time to transmit one MAC data packet (including MAC header, PHY header, and/or tail), an Immediate-ACK frame, a Block-ACK frame, a Block-ACK request frame, the ACK frame timeout, the DIFS time, the SIFS time, the EIFS time, respectively. By the model slot time definition of the Figure 2 we know \( T_{\text{EIFS}} = T_{\text{ACKTIMEOUT}} + T_{\text{DIFS}} - \sigma \), and we can get \( T_{\text{ACKTIMEOUT}} = T_{\text{ACK}} + T_{\text{SIFS}} + \sigma \) according to the IEEE 802.11 protocol. Throughput formula is given here:

\[
S = \frac{E[P]}{E[T]}
\]  

(4)

Which defined as the payload size of the successfully transmitted frame \( E[P] \) in an expected slot duration \( E[T] \).

We firstly compute the expected slot duration \( E[T] \), there are four kinds of situations need to be discussed separately.

First, none of the STAs transmit any frames, the duration called idle slot, let \( T_I \) denotes the length of the duration, so it is natural to know \( T_I = \sigma \), where \( \sigma \) is an idle slot duration.

Second, this is collision case, at least two STAs start to send data block at the same time, let \( T_C \) denotes the collision duration. After the collision, all STAs need to delay the EIFS interval to begin the next backoff procedure and their backoff counter is keeping the last value. As Figure 2 describes the definition of model slot time. So \( T_C = T_{\text{MPDU}} + T_{\text{EIFS}} + \sigma \).

Third, this is error case, only one STA in sending data. Here we consider the error probability of the BAR frame and the BA frame, so in this case we discuss sub-two cases separately: 1) the first MPDU error or the ACK frame error; 2) the first MPDU and the ACK frame are transmitted correctly, but the data block and the BAR frame all errors or the BA frame error. Let \( T_{\text{FM}} \) and \( T_{\text{FA}} \) denote the duration of the sub-two cases separately: 1) sender after waiting for \( T_{\text{ACKTIMEOUT}} \) does not receive the ACK frame correctly shows that it contends failure of channel and then defer \( T_{\text{DIFS}} \) interval, so \( T_{\text{FM}} = T_{\text{MPDU}} + T_{\text{ACKTIMEOUT}} + T_{\text{DIFS}} \), 2) sender after receiving the ACK frame correctly sends the data block and the BAR frame but can’t receive the BA frame correctly, so

\[
T_{\text{FA}} = L_{\text{ba}} \cdot (T_{\text{MPDU}} + T_{\text{SIFS}}) + T_{\text{ACK}} + T_{\text{SIFS}} + T_{\text{BAR}} + T_{\text{EIFS}}
\]  

(5)

Fourth, only one STA in sending data and successful accesses the channel, so it starts to transmit \( L_{\text{BA}} - 1 \) MPDUs and each MPDU between SIFS slot interval. After the transmitter receives the BA frame correctly it starts the next backoff procedure and when the randomly backoff value equal to zero it directly occupies the channel to send the next MPDU. Considering anomalous slots and bit error rate, in fourth case this sub-three cases to be discussed separately: 1) there are multiple successful transmission. Maybe there are some MPDUs transmit errors in the \( L_{\text{BA}} - 1 \) MPDUs, and as the next backoff value is not zero the transmission be terminated; 2) there are multiple successful transmission, as the next backoff value is zero but the transmission be terminated due to the first case of error cases; 3) the multiple successful transmission be terminated due to the second case of error cases. Let \( T_{\text{BLOCK}} \) denotes the duration of a successful transmission that is composed of \( L_{\text{BA}} \) MPDUs, three control frames, each them between SIFS time interval, so

\[
T_{\text{BLOCK}} = L_{\text{ba}} \cdot (T_{\text{MPDU}} + T_{\text{SIFS}}) + T_{\text{ACK}} + 2 \cdot T_{\text{SIFS}} + T_{\text{BAR}} + T_{\text{ba}} + T_{\text{EIFS}}
\]  

(6)

We assume there are \( i \) successful transmission consecutive, the duration for the above sub-three cases can be expressed as follows: 1) \( i \) data blocks transmit time plus a backoff slot, that is \( i \cdot T_{\text{BLOCK}} + \sigma \); 2) \( i \) data blocks transmit time plus an duration of the MPDU or the ACK frame transmits error,
that is \(i \times T_{\text{BLOCK}} + T_{FMBLOCK}\). Next, we are going to calculate the probability of each case. In the first case, none of STAs transmit any frames, the probability that one STA is not transmitting data is \((1-\tau)\), so the probability that \(N\) STAs are all not transmitting any frames is \(P_{T} = (1-\tau)^{N}\). Where \(P_{T}\) denotes the probability of collision, \(P_{S}\) denotes the probability of successful contend channel, \(P_{FM}\) denotes the probability of the first MPDU error or the ACK frame error. \(P_{FA}\) denotes the probability of the data block and the BAR frame all errors or the BA frame error. So these probabilities can be calculated as follows:

\[
\begin{align*}
P_{T} &= (1-\tau)^{N} \\
P_{S} &= N\tau(1-\tau)^{N-1}(1-x) \\
P_{FM} &= N\tau(1-\tau)^{N-1}(p_{E} + (1 - p_{E})p_{ACK}) \\
P_{FA} &= N\tau(1-\tau)^{N-1}(p_{e} - p_{E} - (1 - p_{E})p_{ACK}) \\
P_{C} &= 1 - P_{T} - P_{s} - P_{FM} - P_{FA}
\end{align*}
\] (7)

The fourth case can be regarded as a category of contending channel successful. So we discuss these sub-three cases separately. We take into account anomalous slots, for the first sub-case, the probability that a STA randomly choose the backoff value zero after transmitting the data block over is \(1/W\), the probability of a STA randomly choose the backoff value nonzero is \((W-1)/W\). Therefore, the probability that the STA choose the backoff value nonzero after \(i-1\) successful transmission is:

\[
p_{sm} = \left(1 - \frac{p_{e}}{W}\right)^{-i-1} \left(1 - \frac{1}{W}\right)
\] (8)

Let \(p_{FM} = p_{E} + (1-p_{E})p_{ACK}, p_{FA} = p_{e} - p_{FM}\), for the second sub-case, the STA after \(i-1\) successful transmission randomly chooses backoff value zero, but contend failure of the channel by the MPDU error or the ACK error, the probability can be expressed as:

\[
p_{sm} = \left(1 - \frac{p_{e}}{W}\right)^{-i} \left(\frac{p_{FM}}{W}\right)
\] (9)

For the third sub-case, the probability can be expressed as:

\[
p_{sm} = \left(1 - \frac{p_{e}}{W}\right)^{-i} \left(\frac{p_{FA}}{W}\right)
\] (10)

Therefore, taking into account the anomalous slots, the average successful transmission time \(T_{S}\) can be expressed as:

\[
T_{S} = \sum_{i=1}^{\infty} p_{sm} \times (i \times T_{\text{BLOCK}} + \sigma) + \sum_{i=1}^{\infty} p_{sm} \times i \times T_{\text{FM}} + \sum_{i=1}^{\infty} p_{sm} \times i \times T_{\text{FA}}
\] (11)

so simplification it can be obtained:

\[
T_{S} = \frac{W \times T_{\text{BLOCK}} + (W-1) \times \sigma + p_{FM} \times T_{FM} + p_{FA} \times T_{FA}}{W - 1 - p_{r}}
\] (12)

Therefore, the average time of a model slot can be expressed as:

\[
E[T] = P_{T} \times T_{c} + P_{C} \times T_{c} + P_{FM} \times T_{FM} + P_{FA} \times T_{FA} + P_{C} \times T_{S}
\] (13)

After calculating \(E[T]\), we start calculate \(E[P]\). We just need to analyze the fourth situation and assume that these are \(j\) MPDUs errors in \(i\) data blocks. These \(j\) MPDUs transmit errors only in these \(i \times (L_{BA} - 1)\) MPDUs, so the successfully transmitted valid frame \(E[P]\) in an erroneous case is:
In this paper, we introduced an analytical model that takes into account the effects not only collisions and transmission errors but also anomalous slots and the freezing of backoff counter for the Block-ACK mechanism. Based on the Markovian techniques, the analytical model for Block-ACK mechanism is established in order to measure the saturation throughput. We implement a
saturated version of the Block-ACK mechanism in the NS-2 simulator and validated our analytical model with NS-2 simulations. From Figure 4, we can see our analytical result is very close the simulation result. This aggregation size of the data block and the channel bit error rate are the two main factors that affect the throughput of system.

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