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Throughput Analysis of Block-Ack in IEEE 802.11n

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Abstract—**This article provides a saturation throughput analysis of IEEE 802.11n when Block-ACK is adopted. In contrast to the previous models, our model gives more accurate results owing to taking into account the freezing of backoff counter and anomalous slots. Simulation results show the accuracy of our model.**

Keywords-IEEE 802.11n, CSMA/CA, Block-ACK

I. INTRODUCTION

The MAC layer of IEEE 802.11 employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with binary exponential backoff, called Distributed Contention Function (DCF). Numerous applications over IEEE 802.11 networks have emerged. At the same time, the demand for high-speed IEEE 802.11 networks has been dramatically increasing. Recently, the IEEE 802.11n [1] has been published and its transmission data rate is up to 600Mbps due to the adoption of MIMO technology. However, the significant increasing of data rate doesn't provide the corresponding increasing of MAC layer's throughput. This performance mismatch is caused by the high MAC overhead, such as interframe space (IFS) and per-frame acknowledgement (ACK).

In order to reduce the high MAC overhead, a new ACK scheme, Block-ACK, was first introduced in IEEE 802.11e [2]. Differentiated from the per-frame ACK scheme, the Block-ACK scheme doesn't send the ACK frame for each data frame. Instead, the transmitter firstly sends a group of data frames and then Block-ACK scheme sends only one ACK frame to acknowledge the group of data frames. Owing to the reduction of ACK frames, the MAC overhead caused by IFS and ACK frame shall be greatly reduced. Accordingly, the MAC throughput will be dramatically increasing. The increasing shall be more significant in IEEE 802.11n due to its higher data rate than that of IEEE 802.11e. In this article, we investigate the performance enhancement of Block-ACK in IEEE 802.11n.

The performance of Block-ACK has been analyzed by some researchers [3, 4]. Almost of them extends the analytical model, a bi-dimensional Markov model proposed in [5] into the Block-ACK case. Although these models provided an accurate results, some details of IEEE 802.11 protocol have been neglected by them. The distinguished detail is the freezing of backoff counter. Another detail is those slots called anomalous slots and firstly introduced in [6] in detail. The anomalous slots can be explained as follows: since the backoff counter is decreased only during idle slots, the slots immediately following a successful transmission shall be occupied by the transmitting station (STA) if the STA chooses the value 0 as the next backoff counter. Thus, those slots are anomalous. A more accurate model was introduced to account for both the presence of anomalous slots and the freezing of backoff counter [6]. In order to analyze the performance of Block-ACK, the channel bit error have to be taken into account. However, an ideal channel was still assumed in Tinnirello's model [6]. We have proposed one model to compute the throughput of IEEE 802.11n under the non-ideal channel in [7], but it doesn't account for the Block-ACK.

To our knowledge, there are no contributions on performance analysis of Block-ACK by taking into account both the backoff counter frozen and the anomalous slots. In this article, we introduce a mathematical model which extends the approach in [7] by incorporating the Block-ACK scheme. Saturation throughput is calculated by our new model. Using NS-2 simulation results, we validate our mathematical model.

II. BLOCK-ACK SCHEME

Before using the Block-ACK scheme, the transmitter and receiver have to firstly exchange the add Block-ACK request frame (ADDBA-REQ) and add Block-ACK response frame (ADDBA-RSP) in order to set up this new acknowledgement policy. After such an initialization, A data block of multiple MPDUs are transmitted and acknowledged by a Block-ACK frame (BA). In the initial setup phase, the maximum number of MPDU in a data block is determined by the re-ordering buffer size of the receiver. Note that, in this article, we call the original ACK scheme as immediate ACK scheme (Imm-ACK) because Imm-ACK scheme responds a ACK frame after each MPDU is received.

The frame exchange procedure of Block-ACK scheme is illustrated in Figure1. Basically, the Block-ACK scheme allows a number of MPDUs to be transmitted one by one and each MPDU is separated by a SIFS interval. When the transmitter finishes to transmit the data block, it sends a block ACK request frame (BAR) to inform the receiver the transmission finish and request the BA frame. Once the receiver is informed to respond the ACK frame, it sends the single BA frame to acknowledge the data block. The BA frame is an aggregated ACK frame which stores information about the reception of corresponding MPDUs by using a bitmap. Both the BAR frame and BA frame are transmitted at the same transmission rate that is used for the corresponding data frame transmissions.

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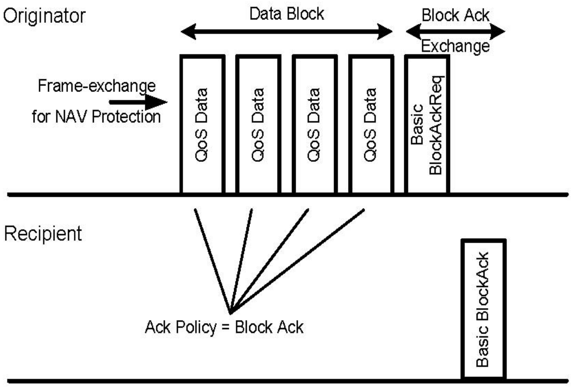

Figure 1. A Typical BLOCK-ACK Sequence [1]

III. MARKOV CHAIN

Our analysis assumes that the network consists of n contending STAs and that each STA has always a packet ready for transmission. Each MPDU has the same packet size Ldata and All STAs adopts the same the data block size Nba (i.e., the number of MPDUs in a data block). We also assume that the wireless channel is a Gaussian channel, in which each bit has the same bit error probability (BER), and bit errors are identically and independently distributed over the whole packet.

It is easily understood that the Block-ACK scheme has the same backoff procedure of contention window as the immediate ACK scheme. Thus, we use the same the Markov model as proposed in [7]. The Markov model is based on a discrete time, that is, the radio medium is segmented into a sequence of model slot times. A model slot time is the time interval between two consecutive backoff counter decrements of a non-transmitting STA, as illustrated in Figure2.

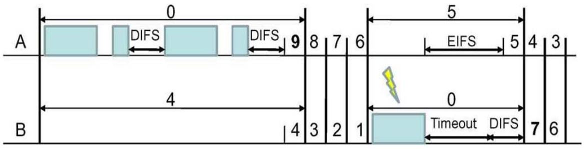

Figure 2. Slot Definition [6]

Given a tagged STA, a bi-dimensional Markov chain (s(t);b(t)) is developed where b(t) and s(t) represent the value of backoff counter and the backoff stage at model slot time t, respectively. The Markov chain is shown in Figure3 as the same chain in [7]. Two stages 0+ and 0- have to be differentiated due to the fact that the backoff counter. belongs to different ranges. Specifically, the backoff counter belongs to the range [0;W-2] after a successful transmission (stage 0+) and to the range [0;W-1] after a packet drop (stages 0-) [6]. One example is also shown in Figure2. After two successful transmissions, STA A starts the next model slot (time t +1) with the value 8 of backoff counter because the initial value 9 of backoff counter belongs to the last model slot (time t).

In Figure3, pf stands for the collision and/or error probability that a transmitted packet experiences and pe is the probability that a MPDU or an Imm-ACK frame (packet size Lack) suffers errors. We assumes that pf is constant and independent of the number of collisions or errors a packet has suffered in the past. Let τ be the probability that a STA transmits in a randomly chosen slot time and pc be the packet collision probability. Thus,

$$\begin{cases} p_c = 1-(1-\tau)^{n-1} \\ p_e = 1-(1-BER)^{L_{data}}(1-BER)^{L_{ack}} \\ p_f = 1-(1-p_c)(1-p_e) \end{cases} \tag{1}$$

We can use the following equation (2) to describe the backoff window varying procedure.

$$W_j = \begin{cases} 2^j W, & j\in[0,m-1], R>m \\ 2^m W, & j\in[m,R], R>m \\ 2^j W, & j\in[0,R], R\le m \end{cases} \tag{2}$$

where CWj denote the contention window in the jth retry/retransmission. Let CWmin be the minimum contention window, CWmax be the maximum contention window, W=CWmin+1 and Wj=CWj+1, m=log2[(CWmax+1)/(CWmin+1)] and R be the retry limits of one MPDU.

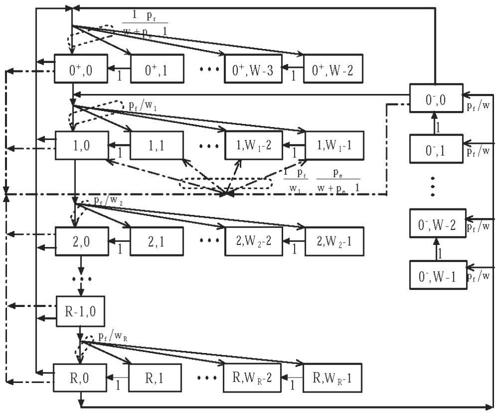

Figure 3. State transition diagram under error-prone channel [7]

Let Ω=pe/(W+pe-1). Owing to the chain regularities, by imposing the normalization condition, we can solve the Markov chain and obtain the τ. The detail computation process can be referred in [7].

$$\tau = \frac{2(1-p_f^{R+1})}{(1-p_f)\left(\sum_{j=1}^{R}(W_j+1)\left[\Omega p_f^{j-1}+(1-\Omega)p_f^{j}\right]+W+1-(1-\Omega)(1-p_f^{R+1})\right)} \tag{3}$$

IV. SATURATION THROUGHPUT

Let δ, TMPDU, Tba, Tbar, TACK, ACKtimeout, SIFS, DIFS, and EIFS denote duration of an empty slot time, the time to transmit one MAC data packet (including MAC header, PHY header, and/or tail), the time to transmit a Block-ACK frame, a Block-ACK request frame, an Imm-ACK frame, the ACK timeout, the SIFS time, the DIFS time, and the EIFS time, respectively. For simplification, we assume EIFS=ACKtimeout+DIFS-δ. In fact, it is true when the basic rate is 1 Mbps. Also, we can get ACKtimeout=SIFS+TACK+δ according to the IEEE 802.11 protocol.

Before transmitting a data block of Nba MPDUs, the transmitter must firstly send the first one MPDU of the data block to contend the channel. If the first MPDU is successfully transmitted, then the transmitter shall occupy the channel to send the remaining MPDUs. Thus, two cases must be differentiated. The first one is that the first MPDU is successful transmitted. For this case, the transmission time Tblock of a data block consists of one MPDU transmission procedure (including the SIFS and Imm-ACK frame), Nba-1 MPDUs transmission (plus SIFS) and the corresponding transmission time of Block-ACK request frame and Block-ACK frame plus an extra DIFS interval for a successful transmission. The second one is that the first MPDU is failed to be transmitted so that the transmitter can't occupy the channel. The second case is caused by two events, a MPDU collision and/or a transmission error occurred when transmitting the MPDU. Based on the DCF, it can readily obtain a collision time Tc and a failed transmission time Tf.

$$\begin{cases} T_{block} = N_{ba} * (T_{MPDU} + SIFS) + T_{ACK} + T_{bar} + T_{ba} + DIFS \\ T_c = T_{MPDU} + EIFS \\ T_f = T_{MPDU} + ACK_{timeout} + DIFS \end{cases} \tag{4}$$

Five different events will happen in one model slot: 1) All STAs are during backoff decrement; 2) There are multiple data block transmissions (this is due to anomalous slots); 3) One or more data block transmissions are followed by a failed MPDU transmission (MPDU error or Imm-ACK error); 4) One MPDU collision occurs; 5) A failed MPDU transmission happens. The duration of one model slot is different for each event: 1) the duration is the time δ; 2) the duration is multiple (i) data block transmission times plus an extra backoff slot, iTblock+δ; 3) the duration is multiple (i) data block transmission times plus a failed MPDU transmission time, iTblock+Tf; 4) the duration is a MPDU collision time plus an extra backoff slot Tc+d=Tf; 5) the duration is a failed MPDU transmission time Tf .

The probability of the first event is (1-τ)n because all STAs are waiting for transmission. After the successful transmission of the first MPDU in a data block, either the second or the third event must occur. Let Pb=1-(1-τ)n denote the probability that there is at least one transmission in a model slot time and Ps=nτ(1-τ)n-1(1-pe) denote the probability that there is at least one data block transmission in a model slot time. Then, the throughput S can be expressed as

$$S = \frac{P_s \overline{E[P]}}{(1-P_b)\delta + P_s \overline{T_s} + (P_b - P_s) T_f} \tag{5}$$

where $\overline{E[P]}$ denotes the average payload size of successful transmissions and $\overline{Ts}$ is the average model slot duration which includes at least one data block transmission.

$$\begin{cases} \overline{E[P]} = \dfrac{W}{W + p_e - 1} \cdot \left[(N_{ba} - 1) \cdot (1 - BER)^{L_{data}} + 1 \right] \cdot P \\ \overline{T_s} = \dfrac{1}{W + p_e - 1} (W T_{block} + p_e T_f) + \delta \end{cases} \tag{6}$$

V. MODEL VALIDATION

We use the simulation tool NS-2 to validate our model. Except for the special statement, all the PHY and MAC parameters are compliant with the 802.11n standard. Two scenarios, moderate channel error (BER=10-6) and very noisy channel (BER=10-5), are investigated. The payload size of one MPDU is 2048Bytes. From the Figure4, our model can predict the DCF performance accurately by taking into account the anomalous slots and the freezing of backoff counter. Some parameters are defined as Rate=300Mbps, CWmin=15, CWmax=1023, Nba=10 and R=7.

VI. SUMMARIES

This paper proposed a bi-dimensional Markov chain to analyze the throughput of block-ACK. Based on the NS-2 simulation, we can see that the analytical results is very close to the NS-2 simulation results. Further, the block-ACK can significantly improve the performance. The improvement is determined by the data block-size. The larger the block-size is, the higher the improvement is. However, the block-ACK induces the re-ordering action at the receiver. This induction may result in the larger delay. Thus, how to analyze the delay performance of block-ACK is our next step.

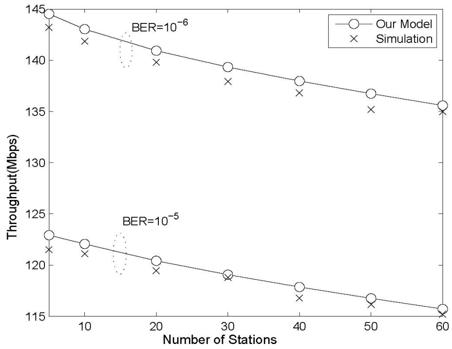

Figure 4. Model Validation

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