ACK Scheme in a Noisy Channel

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***Abstract*— A Block ACK (BTA) scheme has been proposed in IEEE 802.11e to improve medium access control (MAC) layer performance. It is also a promising technique for next-generation high-speed Wireless LANs (WLANs) such as IEEE 802.11n. We present a theoretical model to evaluate MAC saturation throughput of this scheme. This model takes into account the effects of both collisions and transmission errors in a noisy channel. The accuracy of this model is validated by *NS-2* simulations.**

***Index Terms*— IEEE 802.11, IEEE 802.11e, wireless LAN, medium access control, Block ACK, saturation throughput**

I. Introduction

The widespread use of multimedia applications has created new requirements upon the underlying wireless LANs (WLANs). To meet these requirements, people are seeking solutions mainly in two directions: very high-speed techniques and quality-of-service (QoS). The very high-speed solutions are designed for improving effective bandwidth which can be shared by the upper layer applications. The QoS solutions are proposed to provide differentiated services for applications with diverse demands. Recently, the IEEE 802.11 Working Group has created task groups 802.11n [4] and 802.11e [3] to standardize the efforts in corresponding areas.

At the MAC layer, the basic scheme of WLANs is distributed coordination function (DCF) which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism.

A. The DCF scheme

In the legacy DCF scheme, a station (STA) transmits a frame after it has observed an idle medium for a distributed inter-frame space (DIFS) plus a backoff duration. If this frame is received correctly, then the receiver sends back an acknowledgment (ACK) after waiting for a short inter-frame space (SIFS) period, which is the interval needed by the physical (PHY) layer to turn from receiving to transmission state. All the other STAs defer channel contention until the end of the ACK transmission. After that, the receiver and all the other STAs defer a DIFS duration before counting down their backoff counters for the next round of transmission. Such a successful transmission cycle is shown in Fig.2(a).

Collisions and errors make the MAC layer protocol complicated. In this paper, we define a *collision* as the event that at least two STAs start transmission at the same time and the receivers can not decode any frames correctly. We define an *error* as the event satisfying the following two conditions at the same time. First, there is one and only one STA transmitting but the channel is so noisy that the receiver can not decode the whole frame successfully; Second, although PHY has detected errors, it still completes the reception and transfers the received frame to MAC. According to this definition, an *error* in this paper is a MAC layer instead of a normally used PHY concept[1].

In the case of collisions or errors, the receivers and all the other STAs can not decode any frames and do not send back ACKs. The receivers defer their own attempts for an EIFS duration after waiting until the end of the current transmission. The duration of EIFS is the sum of SIFS, DIFS and an ACK transmission interval, i.e., $T_{EIFS} = T_{SIFS} + T_{PHYhdr} + T_{ACK} + T_{DIFS}$. All the notations used in this paper are listed in Table II. The senders wait for the potential ACKs until the end of ACK timeout, and then defer a backoff interval before retransmission.

The length of the backoff period is the product of the slot time[2] and a random number uniformly chosen from the range of $[0, CW-1]$, where CW is the current contention window size. CW is doubled after each failure transmission until the maximum contention window size CW_{max} is reached. After each successful transmission, CW is reset to the minimum contention window size CW_{min}, thus $CW_{min} < CW < CW_{max}$ [1].

B. Motivation

In a CSMA/CA based scheme, MAC and PHY overhead is the main reason for system inefficiency. The overhead refers to backoff, DIFS, ACK, SIFS and PHY layer header. On the one hand, backoff leads to collisions and idle slots due to its randomized characteristic. Therefore, much work has been done to optimize the backoff process [7], [11], [19]. On the

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[1]In reality, errors may be also due to collisions if PHY is able to receive the transmission of multi-users simultaneously or there are hidden terminals. Then an *error* can be defined as the event that although the receiver's PHY completes a reception, the frame that MAC received still contains errors. A *collision* can be defined as the event that the receiver can detect the coming signals but the reception is always interrupted.

[2]Slot time is the unit of backoff process, its value in the idle case depends on the duration that is required by different PHY techniques (e.g. slot time is 9 μs for OFDM based 802.11a) to detect the medium state. If there is ongoing transmission, the slot time corresponds to the duration in which the channel is sensed busy.

	802.11a	802.11n
SIFS (μs)	16	16
Slot time (σ) (μs)	9	9
DIFS (μs)	34	34
PHYhdr (μs)	20	20
CW_{min}	16	16
Propagation delay (δ) (μs)	1	1
Symbol delay (μs)	4	4
PHY rate (Mbps)	6	54·k (k=2,3,...)
Retry limit	4	4

TABLE I

PHY/MAC PARAMETERS.

n	Number of STAs
T_{SIFS}	Time duration of SIFS
T_{DIFS}	Time duration of DIFS
T_{EIFS}	Time duration of EIFS
T_f	Time duration to transmit a frame in BTA
T_{data}	Time duration to transmit a frame in DCF
T_{bar}	Time duration to transmit a BAR frame
T_{ba}	Time duration to transmit a BA frame
T_{ack}	Time duration to transmit an ACK frame
T_{PHYhdr}	Time duration for PHY header
δ	Propagation delay
σ	Idle slot duration
L_{pld}	MAC layer payload size in BTA (bytes)
L_f	MAC layer frame size in BTA (bytes)
L_{data}	MAC layer frame size in DCF (bytes)
L_{ack}	MAC layer ACK frame size (bytes)

TABLE II

NOTATIONS.

other hand, in very-high speed networks, even without the problem caused by the randomized backoff, another impact of the overhead is also significant. To manifest this impact, we show the MAC efficiency of the legacy DCF in an ideal case.

In the ideal case, the channel is regarded as perfect, i.e., neither errors nor collisions occur, and in any transmission cycles, there is only one active STA which always has backlogged[3] frames to transmit. The receiver only responds with ACKs, and the other STAs just sense the channel and wait. We can define the average length of the backoff as $T_{\overline{CW}} = (CW_{min} - 1) \cdot \sigma/2$, where σ stands for the idle slot duration. Then the ideal throughput S_{ideal}^{DCF} can be defined as in (1) [18]. The notations are listed in Table II and the parameters are listed in the third column in Table I.

$$S_{ideal}^{DCF} = \frac{8 \cdot L_{data}}{T_{DIFS} + T_{\overline{CW}} + T_{data} + T_{SIFS} + T_{ACK} + 2\delta}. \quad (1)$$

Using (1), we illustrate in Fig. 1 the MAC efficiency while the PHY rate is increased from 54 to 432 Mbps. Here, the MAC efficiency represents the ideal throughput normalized to the PHY rate. As we can see, the efficiency decreases dramatically as the PHY rate increases. Moreover, even though the PHY rate is infinitely high, the MAC efficiency is still bounded by a maximum value [18].

To mitigate this overhead inefficiency, a Block ACK (BTA) scheme has been proposed in 802.11e [3] standard and 802.11n proposals (e.g., [4]). In the BTA scheme, a block of frames destined to a same receiver is allowed to be transmitted without being acknowledged. After the transmission block, the sender initiates a Block ACK Request (BAR) frame to enquire the number of frames that have been received successfully. The receiver then responds with a Block ACK (BA) frame. The efficiency of the BTA scheme comes from the fact that the overhead is greatly reduced, because DIFS and backoff only occur before the first frame of the block and only one ACK is used for all the frames in the block.

C. Related Work

A previous version of the BTA scheme known as Burst Acknowledgement has been studied in [16]. In the Burst Acknowledgement scheme, only the first frame in a transmission burst contends for the channel access, the other frames are transmitted after deferring a SIFS interval. But after each frame, an ACK is sent back by the receiver. In [18], Xiao and Rosdahl investigate the ideal case throughput and delay of the BTA scheme. In [14], the authors analyze the saturation throughput of the BTA scheme in an infrastructure network with the assumption that the channel is error-free.

[3]A frame is said to be backlogged if it is in the queue between the MAC and its upper layer waiting to be transmitted.

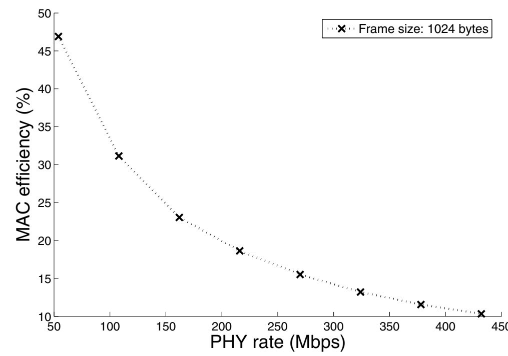

Fig. 1. Legacy DCF throughput in the ideal case with a 1024-byte frame size. The x-axis represents the PHY rate. The y-axis represents the ratio of the ideal throughput to the PHY rate.

D. Contributions

To the best of our knowledge, none of the existing work has focused on the ad-hoc performance of the BTA scheme in noisy environments. Thus, we developed an analytical model (BTA-MODEL) for this aim. The BTA-MODEL is an extension of Bianchi's work [6] and our prior model [13]. It provides a simple MAC layer throughput analysis based on a saturation assumption that the MAC layer has always backlogged frames. The key observation that underpins our extension is that each transmission block can be treated as a single frame of DCF. The validity of the BTA-MODEL is verified through *NS-2* simulation results.

E. Organization

The remainder of the paper is organized as follows. In Section II, we introduce the BTA scheme. Then the analytical model is described in Section III. Section IV presents our implementation of the BTA scheme and the corresponding simulation results. Finally Section V concludes this paper and introduces future work.

II. The BTA Scheme

In the BTA scheme, a block of frames sent to the same receiver is allowed to be transmitted without being acknowledged, each frame is separated by a SIFS period. As shown in Fig.2(b), a backoff is generated for a transmission block instead of a single frame. After the block, a BAR frame is initiated by the sender to enquire which frames have been received successfully, and then a BA frame is sent back by the receiver to answer this enquiry.

The BTA scheme is designed for improving the channel efficiency by aggregating several ACKs together. The sender only contends for the channel access before the first frame of a block. If it wins the channel contention and starts transmission, the sender sends out a whole block and a BAR frame, and then stops to wait for the BA frame. Upon receiving the BA frame correctly, the sender should defer a DIFS interval and a backoff process before sensing the channel again. Meanwhile, all the other STAs should wait until the end of the BA transmission, and then defer another DIFS interval before counting down their backoff counters for the next round of transmission.

In the case of collision, at least two STAs start transmission in a slot, each of them sends out a whole block and a BAR frame, and then waits for the BA frame. The receivers shall not send back the BA frames if they can detect the collisions, otherwise the BA frames will be initiated. In both cases, the senders can not receive the BA frames successfully because collisions also happen for the BA frames, and then the senders have to retry their transmission again.

In the erroneous case, the sender sends out a whole block and a BAR frame. The receiver then sends back a BA frame to indicate which frames are corrupted. If the sender receives the BA frame successfully, those correctly transmitted frames in the block will be removed from the sending queue and a new block will be constructed for next round of transmission.

It can be seen that the BTA scheme operates in a similar way to the legacy DCF. In particular, we may regard a block in BTA as a frame in DCF because both of them are treated as a unit of operation. This understanding suggests that it is possible to extend previous analysis which was designed for the legacy DCF to study the BTA scheme.

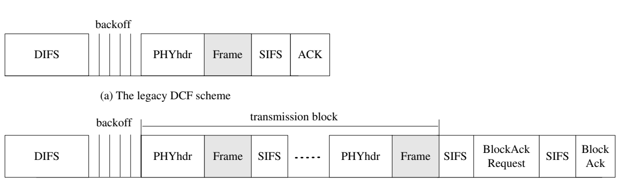

Fig. 2. The DCF and BTA schemes.

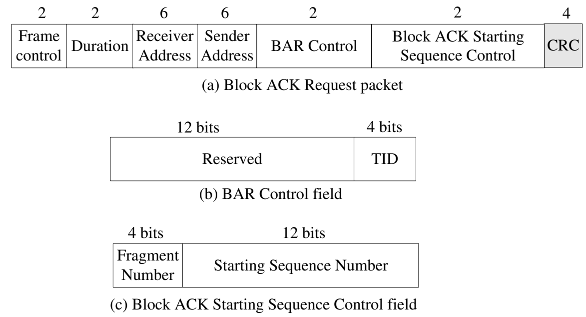

Fig. 3. Format of the Block ACK Request frame.

A. Frame formats

Fig. 3(a) shows the format of a BAR frame. There are two new fields in the BAR frame. The *BAR control* field is shown in Fig. 3(b). This field is used for QoS negotiation between MAC and its upper layer. The *Block ACK Starting Sequence Control* field is shown in Fig. 3(c). The last 12 bits of this field are used to record the first frame's sequence number in a block, the first 4 bits are reserved for further usage.

To inform the sender which frames have been lost in a block, a *Block ACK Bitmap* field is designed in the BA frame as illustrated in Fig. 4. It is a 128-byte field, thus it supports up to 128*8=1024 frames in a single block. The *Block ACK Starting Sequence Control* field is used to indicate to which BAR this BA frame responds.

B. Discussion

In the BTA scheme, an appropriate mechanism is needed to negotiate the number of frames supported in a block. In an infrastructure mode, this initialization can be controlled by the Access Point (AP). AP periodically polls all the STAs in its management range to broadcast the start time and the number of frames in one block. All the STAs just accept AP's assignment. In an ad-hoc network, however, the BTA scheme has to be initialized in a distributed manner. To this aim, 802.11e [3] proposes to use a four-way handshake. Before each block transmission, the sender sends an *Add Block ACK Request* frame to the receiver which should respond with an ACK, and then the receiver sends an *Add Block ACK Response* frame to the sender which should respond with an ACK.

Second, BTA can be used as a solution for the multi-rate problem in CSMA/BA based networks. Recently, [9] and [15] have showed that a CSMA/CA based network distributes transmission probabilities fairly amongst all the STAs. Thus, if STAs have different rates, the final throughput for all of them

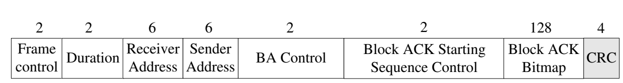

Fig. 4. Format of the Block ACK frame.

will be the same. This fairness is in fact not fair for the fast STAs because they should achieve higher performance than the low ones. In this case, BTA can be used for the fast STAs to transmit multiple frames once they obtain the transmission opportunities.

III. An Analytical Model

In this section, we present an analytical model to compute the saturation throughput for the BTA scheme.

We consider an ad-hoc network where all the STAs can hear each other. In such an area, collisions occur only when at least two STAs start transmission at exactly the same time. Transmission errors occur when only one STA is transmitting in a given slot, but the transmission can not be received correctly because of channel noise. We assume that the PHY headers are always transmitted successfully given the fact that they are usually transmitted at the basic hence the safest rate [1]. We also assume that the transmission of the BAR and BA frames is always successful.

A. Saturation Throughput

Based on previous work [6], [17] and [13], we have designed an analytical model for the BTA saturation throughput S_{BTA}, which is defined as the payload size of the successfully transmitted frame $E[L_{pld}]$ in an expected slot duration $E[T]$.

$$S_{BTA} = \frac{E[L_{pld}]}{E[T]}. \tag{2}$$

We first compute the expected slot duration $E[T]$. There are four types of durations in the BTA scheme as shown in Fig.5.

First, if none of the STAs transmit any frames, they all wait for a duration $T_i = \sigma$, where σ corresponds to the idle slot interval.

Second, let T_S denote the duration during which a whole block is transmitted successfully. In this case, only one STA transmits and its transmission is always successful. The channel state shall be kept busy in a duration which is equal to the duration of a block of frames' transmission plus $(N_b - 1)$ SIFSs, a BAR and a BA transmission, where N_b denotes the number of frames in a block.

Third, let T_E be the duration in which at least one frame in a block is corrupted due to the channel errors. The sender shall not stop transmission and the receiver shall respond with a BA frame. Then the other STAs defer a block and a DIFS duration.

Fourth, let T_C denote the collision duration in which at least two STAs start transmission simultaneously. No BA frames are initiated by the receivers in this situation. All the other STAs except the senders and the receivers defer for an EIFS ($T_{EIFS} = T_{SIFS} + T_{PHYhdr} + T_{ba} + T_{DIFS}$) interval. The slot durations can be expressed as follows.

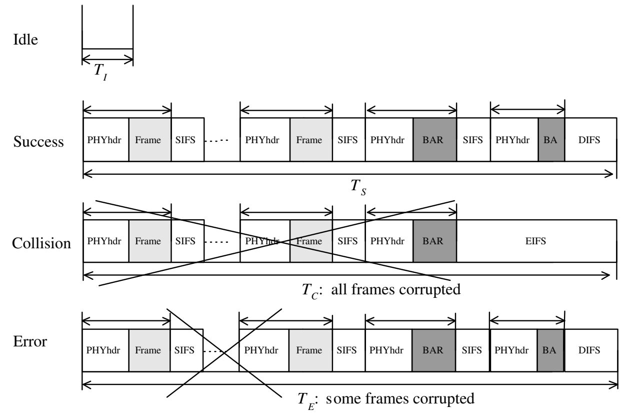

Fig. 5. Time durations in the BTA scheme

$$\begin{aligned}
T_I &= \sigma \\
T_S &= N_b \cdot (T_f + T_{SIFS}) + T_{DIFS} + \\
&\quad (T_{bar} + T_{SIFS} + T_{ba}) + (N_b + 2)(T_{PHYhdr} + \delta) \\
T_E &= T_S \\
T_C &= N_b \cdot (T_f + T_{SIFS}) + T_{EIFS} + \\
&\quad (T_{bar} + T_{SIFS} + T_{ba}) + (N_b + 1)(T_{PHYhdr} + \delta).
\end{aligned}$$

We then turn to calculate the corresponding possibilities for the slot durations. Let τ and n denote a STA's transmission probability in a slot and the number of STAs in the system respectively.

Firstly, for an idle slot, a single STA does not attempt transmission with probability $(1-\tau)$, and then all the n STAs in the system keep silent with probability $P_I = (1-\tau)^n$ as shown in (3).

Secondly, let p_e^{bta} denote a single STA's error probability for an entire block, then the successful probability can be expressed as in (4). Similarly, we get the system error probability P_E in (5).

Finally, since these four events (idle, success, collision and error) are mutually exclusive [10], collision probability for a system can be defined as in (6).

$$P_I = (1-\tau)^n \tag{3}$$

$$P_S = n \cdot (\tau(1-\tau)^{n-1}) \cdot (1 - p_e^{bta}) \tag{4}$$

$$P_E = n \cdot (\tau(1-\tau)^{n-1}) \cdot p_e^{bta} \tag{5}$$

$$P_C = 1 - P_I - P_S - P_E. \tag{6}$$

Let p_e denote the Packet Error Rate (PER) of a frame. The probability p_e^{bta} can be expressed as:

$$p_e^{bta} = 1 - (1 - p_e)^{N_b}. \tag{7}$$

p_e can be computed if the bit error distribution is given. We use the discrete-time, memory-less Gaussian channel as an example. In such a channel, the bit errors independently and identically distributes over a frame [8]. Let L_f and p_b denote the frame size and the bit error rate (BER) respectively, then p_e is defined as:

$$p_e = 1 - (1 - p_b)^{L_f}, \quad (8)$$

where the p_b is assumed to be known by the MAC layer. In reality, it can be measured by the PHY layer. If the p_b measurement is not available, then p_e can be calculated instead.

Although the memory-less Gaussian model is unable to capture the fading characteristics of the wireless channel, it is widely used to model wireless channels due to its simplicity. Moreover, if interleaving is employed, the BER will become Gaussian-like.

So far we have known all the variables except τ in (3-6). Let p_f denote the probability of doubling contention window after a failure transmission. The probability τ can be expressed as a function of p_f, and we can find another function of τ for p_f. Both of them are obtained from a Markov chain that is similar to the one in Bianchi's paper [6]. We will explain this Markov chain in section III-B.

Finally, all the variables in (3-6) have been defined. The saturation throughput S_{BTA} can be expressed as:

$$S_{BTA} = \frac{P_S \cdot L_f + P_E \cdot E[L_f]}{P_I T_I + P_S T_S + P_E T_E + P_C T_C}, \quad (9)$$

where $E[L_f]$ stands for the expected frame size successfully transmitted in an erroneous case. Let i denote the number of the corrupted frames, based on the same time-less Gaussian assumption the $E[L_f]$ can be expressed as:

$$E[L_f] = \sum_{i=1}^{N_b} \binom{N_b}{i} \cdot (p_e)^i \cdot (1 - p_e)^{N_b - i} \cdot (N_b - i) \cdot L_f. \quad (10)$$

B. The Markov Chain

In [6], Bianchi first introduced a bi-dimensional stochastic process $\{s(t), b(t)\}$ to model the backoff behavior of the legacy DCF. Process $b(t)$ represents the backoff counter, and it is decremented at the beginning of each slot. For an idle slot, the time scale of $b(t)$ corresponds to a real slot time. In a collision slot, however, $b(t)$ is frozen for the duration of this transmission. Whenever $b(t)$ reaches zero the STA transmits and starts another round of backoff regardless of the outcome of the transmission. The new backoff starts from a value selected randomly from 0 to contention window CW. The CW shall be reset after a successful transmission and be doubled up to a maximum value CW_{max} for corrupted cases. This implies that $b(t)$ depends on the transmission history, therefore is a non-Markovian process. To overcome this, another process $s(t)$ is defined to track the contention window size.

This bi-dimensional stochastic process is a Markov chain under the following two assumptions. First, the transmission probability τ is constant in every slot time. Second, at each transmission attempt, regardless of the number of retransmission, each frame is lost with an independent constant probability p_f.

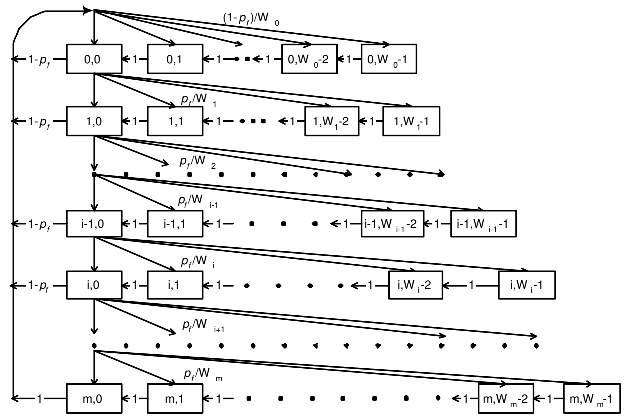

Fig. 6. The Markov chain used in this paper

Under these assumptions, the bi-dimensional stochastic process $\{s(t), b(t)\}$ forms a Markov chain as shown in Fig.6. In this chain, all the states are ergodic because they are aperiodic, recurrent and non-null, thus a stationary solution exists [10]. Given the stationary distribution, we can solve τ and p_f with this Markov chain as follows.

Let us consider the first formula for p_f and τ. In the Markov chain above, p_f stands for the probability that the contention window is doubled because of either collisions or errors. Bianchi's paper assumes there are no errors in the channel, so $p_f = p_c = 1 - (1 - \tau)^{n-1}$ where n stands for the number of STAs in the system. We add the impact of transmission errors in this paper. If the contention window is reset after an erroneous transmission, then $p_f = p_c$; if the contention window is doubled, then $p_f = p_c + p_e - p_c \cdot p_e$ where p_e is defined in (8). In this paper, we reset the contention window after errors occur because errors occur when one and only one STA is transmitting.

Now, we introduce the second formula for p_f and τ. The transmission probability τ in a slot time should be the sum of all the probabilities of the contention window decreases to zero at all the backoff stages. I.e., $\tau = \sum_{i=0}^{m} b_{i,0}$ where m is the maximum backoff stage as defined by $CW_{max} = 2^m \cdot CW_{min}$, and $b_{i,0}$ is the probability of the contention window decreases to zero at the stage i. Bianchi's paper assumes that a frame can be retransmitted infinite times, which is inconsistent with the 802.11 specification [1]. Wu et al. loose this assumption in their work [17]. We use formulas (8) and (9) in [17] to solve $b_{i,0}$.

Finally, with these two formulas, a closed form solution for p_f and τ is formed and both of them can be solved. Therefore, we find the last variable τ required in (3-6).

IV. Evaluation

We implemented the BTA scheme in the network simulator *NS-2* [5] to validate our analytical model. In this section, we introduce the implementation and the simulation results. The experiment parameters are listed in Table I.

First of all, in the *NS* version 2.27 [5] that we used, the PHY headers are transmitted with the same rate as the data part. However, the IEEE 802.11a [2] specifies that the PHY headers should be transmitted within $20\mu s$ no matter what the data part length is. We changed the *NS-2* codes according to the specification.

Second, all the STAs are simply put on a line because topologies have no influences on the analytical results. However, we need to guarantee that there are no hidden terminals in the network. This can be accomplished by assigning enough power for each STA, so that all of them can hear each other.

Third, we need to ensure that all the STAs achieve the same throughput because all of them are modelled by a single Markov chain in the BTA-MODEL (The same requirement is needed in Bianchi's model). To gauge whether this fairness goal is reached in the *NS-2* simulations, we use the Jain's fairness index I [12] which is a real value between 0 and 1. In particular, given n STAs in the system, Jain's fairness index I is defined as:

$$I = \frac{(\sum_{i=1}^{n} S_i)^2}{n \cdot \sum_{i=1}^{n} S_i^2}, \quad (11)$$

where n stands for the number of STAs and S_i stands for the throughput of STA i. When every STA achieves exactly the same throughput, I is equal to 1. In our simulations, we run each test for a duration that is long enough to obtain a fairness index I close to 1. If only one STA happens to dominate the channel entirely, I approaches $1/n$.

Finally, we introduce our implementation as follows. We implemented the BTA scheme by changing the MAC layer running logic, adding a *bitmap array*, a sending queue (*Sq*) and a receiving queue (*Rq*). The *bitmap array* is for recording the number of frames that have been transmitted successfully. The *Sq* and the *Rq* are used to save frames temporarily at the MAC layer. For convenience, let h_{Sq}, t_{Sq}, h_{Rq}, and t_{Rq} denote the head of the *Sq*, the tail of the *Sq*, the head of the *Rq* and the tail of the *Rq* respectively.

The sender stores a frame from the upper layer at the t_{Sq}, and checks whether N_b (the number of frames in a block) frames have been transmitted. If so, it constructs a BAR frame at the MAC layer and transmits it. Otherwise, the first frame at the h_{Sq} shall be popped out and be transmitted.

On reception of a data frame f_j, the receiver checks its correctness and updates accordingly the *bitmap array* whose length is equal to N_b. afterwards f_j is appended at the t_{Rq} if it has not been received before. If f_j has been in the *Rq* but marked as erroneous, the receiver updates its flag. Upon receiving a BAR frame, the receiver responds with a BA frame containing the *bitmap array*. Then the *bitmap array* will be reset for the next round of receiving, and all the correctly received frames at h_{Rq} are transferred to the upper layer.

After receiving a BA frame, the sender removes all the frames that have been received successfully from the *Sq*. The contention window will be reset for both successfully and erroneous transmission.

In the case of collisions, receivers do not initiate the BA frames. After a transmission block, senders wait until the BAR timeout and retransmit the entire block.

A. Numerical Results

First, we show the validity of the BTA-MODEL in Fig.7. The curves for the BTA-MODEL is obtained from (9). The *NS-2* simulation results are obtained by running each test three times with a fairness index $I > 0.90$. To reduce simulation time, the IEEE 802.11a (6Mbps PHY rate) is used to verify the model. From the results we can see that the BTA-MODEL matches the *NS-2* simulations very well.

In the next step, we show the superiority of the BTA scheme by comparing it with the legacy DCF. To this end, a model for the legacy DCF scheme is required. We use the ERR-MODEL that have been developed and validated in our previous work [13]. To compare both schemes, we assume the same conditions for both of them. In particular, the definitions of collision and error are the same, and only the data frames will be corrupted in the case of errors. The BAR and BA frames in the BTA scheme and the ACK frames in the legacy DCF are always transmitted correctly. Meanwhile, the ERR-MODEL has two differences with the BTA-MODEL. First, ACK duration is used instead of the BAR and BA durations. Second, EIFS rather than DIFS is deferred for the erroneous transmission, and $T_{EIFS} = T_{SIFS} + T_{PHYhdr} + T_{ack} + T_{DIFS}$. Consequently, the slot durations for the ERR-MODEL are[4]:

$$\begin{array}{rcl} T_I & = & \sigma \\ T_S & = & T_{data} + T_{SIFS} + T_{ack} + T_{DIFS} \\ & & +2 \cdot (T_{PHYhdr} + \delta) \\ T_E & = & T_{PHYhdr} + T_{data} + T_{EIFS} + \delta \\ T_C & = & T_E. \end{array} \quad (12)$$

The corresponding probabilities are listed in (13). Thus the saturation throughput for the legacy DCF S_{DCF} can be expressed as in (14).

$$\begin{array}{l} P_I = (1-\tau)^n \\ P_S = n \cdot (\tau(1-\tau)^{n-1}) \cdot (1-p_e) \\ P_E = n \cdot (\tau(1-\tau)^{n-1}) \cdot p_e \\ P_C = 1 - P_I - P_S - P_E. \end{array} \quad (13)$$

$$S_{DCF} = \frac{P_S \cdot L_{data}}{P_I T_I + P_S T_S + P_E T_E + P_C T_C}. \quad (14)$$

We then show the comparison results in Fig.8. Here, we use the parameters of the proposed IEEE 802.11n specification. As expected, BTA achieves considerable higher throughput than its legacy alternative when there is more than one frame in a block. If there is only one frame in a block, the inefficiency

[4]The ERR-MODEL in [13] has five time durations because transmission errors of ACK frames are also considered.

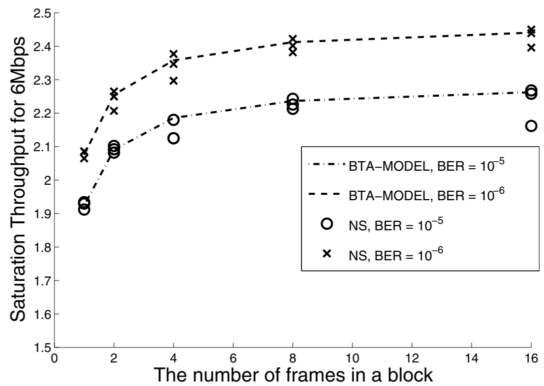

Fig. 7. Comparison of model and simulation results for the BTA scheme with a 1024-byte frame size. The other parameters of the IEEE 802.11a are listed in Table I.

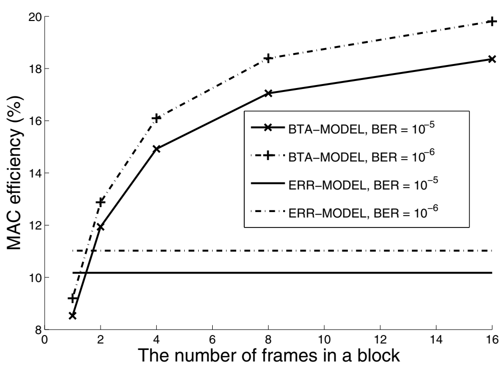

Fig. 8. Throughput: BTA-MODEL vs ERR-MODEL while increasing the number of frames in a block from 1 to 16, and keeping frame size, PHY rate, the number of STAs and retry limit as 1024 bytes, 216 Mbps, 50 and 4 respectively. The other parameters of the IEEE 802.11n are listed in Table I.

of the BTA scheme is due to the fact that two frames (BAR and BA) are used rather than only one frame (ACK) as in the legacy DCF.

Finally, we evaluate the BTA scheme in a dense network where there are many STAs. In such a network, collisions are the main performance obstacle. As illustrated in Fig.9, the BTA scheme always achieves higher throughput than the legacy.

V. Conclusion

In this paper, we introduced an analytical model that takes into account the effects of not only collisions but also transmission errors for the BTA scheme. We implemented a saturated version of the BTA scheme in the *NS-2* simulator and validated the BTA-MODEL with *NS-2* simulations. Then we compared the BTA scheme with the legacy DCF using the analytical models.

As future work, we plan to investigate the delay performance of the BTA scheme in the saturated case, and also the throughput and delay in the non-saturated scenario.

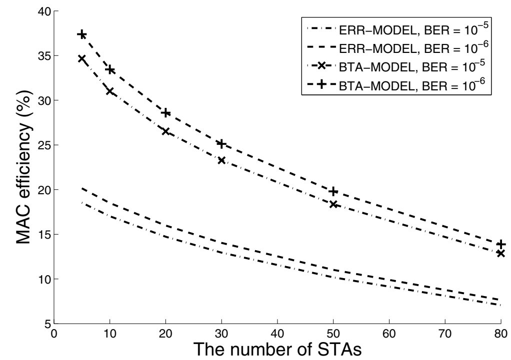

Fig. 9. Throughput: BTA-MODEL vs ERR-MODEL while increasing the number of STAs from 5 to 80, and keeping frame size, PHY rate, frames in a block and retry limit as 1024 bytes, 216 Mbps, 16 and 4 respectively. The other parameters of the IEEE 802.11n are listed in Table I.

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