A Reactive Cross Collision Exclusionary Backoff Algorithm in IEEE 802.11 Network

Subodh Pudasaini[1], Yusun Chang[2] and Seokjoo Shin[1]
[1]Department of Computer Engineering, Chosun University
Gwangju, Republic of Korea
[email:{subodh, sjshin}@chosun.kr]
[2]Communications Systems Center, School of Electrical and Computer Engineering
Georgia Institute of Technology, Georgia, USA
[email: yusun@gatech.edu]
Corresponding author: Seokjoo Shin

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Abstract

An inseparable challenge associated with every random access network is the design of an efficient Collision Resolution Algorithm (CRA), since collisions cannot be completely avoided in such network. To maximize the collision resolution efficiency of a popular CRA, namely Binary Exponential Backoff (BEB), we propose a reactive backoff algorithm. The proposed backoff algorithm is reactive in the sense that it updates the contention window based on the previously selected backoff value in the failed contention stage to avoid a typical type of collision, referred as cross-collision. Cross-collision would occur if the contention slot pointed by the currently selected backoff value appeared to be present in the overlapped portion of the adjacent (the previous and the current) windows. The proposed reactive algorithm contributes to significant performance improvements in the network since it offers a supplementary feature of Cross Collision Exclusion (XCE) and also retains the legacy collision mitigation features. We formulate a Markovian model to emulate the characteristics of the proposed algorithm. Based on the solution of the model, we then estimate the throughput and delay performances of WLAN following the signaling mechanisms of the Distributed Coordination Function (DCF) considering IEEE 802.11b system parameters. We validate the accuracy of the analytical performance estimation framework by comparing the analytically obtained results with the results that we obtain from the simulation experiments performed in ns-2. Through the rigorous analysis, based on the validated model, we show that the proposed reactive cross collision exclusionary backoff algorithm significantly enhances the throughput and reduces the average packet delay in the network.

Keywords: Reactive backoff, cross collision exclusion, distributed MAC, WLAN, IEEE 802.11

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1. Introduction

Sharing a common broadcast channel of a wireless network by multiple stations (STAs) must be guided according to some rules to ensure operational stability of the network. Such rules are collectively known as a Medium Access Control (MAC) protocol. Depending on the network's characteristics (network architecture, application requirements etc.) various MAC protocols have been developed so far [1]. They can be categorized in two classes: one which provisions contention-based access, and the other which provisions scheduled collision-free access to the contending STAs. The contention-based MAC suffers from collisions when multiple STAs access the channel simultaneously. Therefore, a well-designed contention-based MAC protocol should resolve the collisions by incorporating an efficient Collision Resolution Algorithm (CRA). The CRA would provide re-access to the collided STAs in such a way that the probability of subsequent collisions gets minimized. Some popular disciplines of CRA are backoff based algorithms that have been used in Ethernet and WLAN [2], Splitting-Tree based algorithms in CATV [3], and Elimination-Yield based algorithms in HIPERLAN [4].

In the IEEE 802.11 based WLANs, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) combined with a simple CRA, Binary Exponential Backoff (BEB), obtained huge popularity. The CSMA/CA avoids collisions by monitoring channel activities while the BEB resolves those collisions which could not be avoided. The collision resolution functionality of the BEB is very simple. Its simplicity, however, poses significant overheads associated with collision resolution: channel waste time due to packet collisions, and channel idle time due to corresponding backoff delays (pre backoff delay for the collided access and post backoff delay for the next access). Such overheads deteriorate the channel efficiency of the network. Especially, when the network is highly loaded there will be more collisions, and the channel efficiency will drop severely.

An ideal prerequisite for any enhancement proposals in the BEB would be the capability to leverage its performance while maintaining its simplicity intact. Hence, our objective is to devise a backoff scheme, which retains the simplicity of the BEB and reduces channel waste time due to packet collisions. We start with observation of the backoff procedure in the BEB. Whenever a collision is perceived, the BEB proactively doubles the contention window. Such proactive window expansion definitely reduces the subsequent collision chances. It is worth noting that some slots in the beginning of the currently expanded contention window (those which were present in the previous contention window as well) are more collision prone; these slots might have already been picked up by some other STAs before the initiation of the currently considered collision resolution stage. Hence, it would be safe (in terms of collision avoidance) not to select any of the contention slots in the overlapped region. Note that the number of slots in the overlapped region depends on the backoff value selected in the previous contention stage which ended in a collision.

In this paper, we propose a reactive BEB which deterministically nullifies the selection chances of the overlapped contention slots in the adjacent contention stages. Avoiding selection of the overlapped slots eliminates chances of a special type of collision which we refer cross collision (see Section 3 for formal definition). This feature is named as Cross Collision Exclusion (XCE). The supplementary XCE feature along with the other regular collision minimization features in the BEB, make the proposed reactive backoff algorithm superior in terms of better collision resolution. Through the rigorous analysis, we show that the proposed algorithm significantly escalates the throughput and reduces the average packet delay in the network.

The remainder of the paper is organized as follows. In Section 2, an overview of the IEEE 802.11 and some related works on performance enhancement of the backoff algorithm are presented. The proposed reactive backoff algorithm is elaborated in Section 3. An analytical model for numerical performance analysis is presented in Section 4. Model validation and the detailed performance comparision are discussed in Section 5. Finally, we conclude the paper in Section 6.

2. Preliminaries

2.1 Access Mechanisms in IEEE 802.11

The IEEE 802.11 specification [2] covers MAC and physical layer (PHY) issues. It specifies two operating modes for channel access: a mandatory contention-based Distributed Coordination Function (DCF), and an optional scheduling-based Point Coordination Function (PCF). The DCF is based on the CSMA/CA access mechanism. It offers two options for transmitting unicast packets: a mandatory two-way handshaking technique, basic access mechanism, and an optional four-way hand shaking technique, Request To Send/Clear To Send (RTS/CTS) access mechanism. The RTS/CTS based mechanism appears as an enhancement to the basic access mechanism; it reduces contention resolution overhead in terms of channel waste time due to packet collisions.

In the basic access mechanism, each STA which has unicast packet to transmit first monitors the channel activity. If it finds the channel to be idle for a period of time equal to Distributed Inter Frame Space (DIFS), it transmits the packet at the beginning of the immediately following slot. Otherwise, it waits until the channel becomes idle for DIFS period. The STA then computes a random backoff time for which it should defer its transmission. The backoff timer is decreased by one after the channel has been idle for DIFS at the elapse of every idle slot until either the channel becomes busy again, or the backoff timer reaches zero. If the timer has not reached zero and the channel becomes busy, the STA freezes its timer. When the timer is finally decremented to zero, the STA transmits the packet. The intended receiver, if it correctly receives the transmitted packet, confirms the successful reception of the packet by sending a positive acknowledgement (ACK) after a Short Inter Frame Space (SIFS) time. If the source STA does not receive an ACK, it assumes the packet has experienced a collision and updates the contention window according to the BEB rules. Then it sets its backoff counter to a new random value after an Extended Inter Frame Space (EIFS).

In the RTS/CTS access mechanism, short RTS and CTS packets are exchanged between the source and the destination to reserve the channel for data transmission. A STA that has a packet to transmit follows the same process exactly as in the basic access mechanism, however when the backoff counter reaches zero, it sends a special reservation packet called RTS packet. The intended receiver STA responds with CTS packet after SIFS interval. Other STAs who overhear RTS and CTS update their Network Allocation Vectors (NAVs) accordingly. Upon receiving the CTS, the source releases its data packets after SIFS time. The rest of the other remaining processes are identical as in the basic access mechanism.

2.2 Related Work

In general, backoff algorithms can be characterized by three key measures: the expansion/reset factor of the contention window, the probability distribution of contention slot selection, and the update mechanism of the contention window's bounds. Most of the available works on the performance enhancement of the backoff based CRA are thus focused on either independently or jointly customizing these parameters.

Some of the popular schemes that customize the expansion/reset factor of the contention window are Exponential Increase Exponential Decrease (EIED) [5], Multiplicative Increase Linear Decrease (MILD) [6], Double Increase Double Decrease (DIDD) [7], Binary Negative Exponential Increase [8], Logarithmic Increase [9] etc. In comparison to the BEB, EIED enhances throughput and delay performances. Likewise, MILD also enhances throughput when the network is heavily loaded, and DIDD enhances throughput regardless of network load. However, MILD elongates delay when the network is lightly loaded, and DIDD increases delay when the network is heavily loaded. It is noteworthy to mention that none of these schemes are capable of eliminating cross collisions. Gentle Decrease in [10] and Slow Decrease in [11] present an approach to smoothly reset contention window after each successful packet transmission. They reset the contention window to some other suitable window (not to the specified minimum contention window as in BEB). One possible example could be resetting the contention window to half of the present window. Such dynamic reset techniques improve the adaptability of these algorithms to heavy network load. However, since these algorithms modify the BEB in resetting the contention window (keeping contention window updating function intact), they also cannot avoid cross collisions.

Schemes in [12][13][14] and [15] use non-uniform probability distribution for contention slot selection over the optimized contention window. The contention window is optimized according to the estimated number of contending STAs. These schemes generally offer better throughput performance compared to the BEB. However, accurate estimation of the number of contending STAs in the network is not an easy task. The calculated so-called optimal contention window based on the erronomous estimation, in reality, would not be optimal. Hence, these schemes have limitations to be deployed in practice.

The schemes in [16], [17] and [18] have some similarities with the proposed scheme. The schemes in [16] and [18] are similar to the proposed scheme in the regard that they update the lower bound of the contention window. As the proposed scheme does, they also avoid the cross collisions. However, for every contention stage i, they update the lower bound always to $W_i/2$ which is always not required, especially in the situation when j (backoff value selected in the previous contention stage) is large. In the present scheme, we make a dynamic lower bound which adapts to j. As a result, it avoids the cross collision with the least possible average backoff delay. The scheme in [15] has similarity with the proposed scheme in using history backoff value (memory property) to manage the next contention round. Characteristic comparison of these schemes is presented in **Table 1**.

Table 1. Characteristic comparison

<table>
<tr><th>Characteristic</th><th colspan="2">Schemes in [14] and [20]</th><th colspan="2">Scheme in [15]</th><th colspan="2">Proposed Scheme</th></tr>
<tr><td rowspan="2">CW in i-th stage</td><td>Lower</td><td>Upper</td><td>Lower</td><td>Upper</td><td>Lower</td><td>Upper</td></tr>
<tr><td>$W_i/2$</td><td>W_i-1</td><td>0</td><td>$(\alpha.W_{i-1}-1)$</td><td>$W_i/2-1-j$</td><td>$W_{i-}1$</td></tr>
<tr><td>CW scaling factor</td><td colspan="2">Logically same as in BEB but avoids selection of earlier slots up to Wi/2-1</td><td colspan="2">Scaling factor α is obtained with reference to the selected backoff value (j) in previous contention stage</td><td colspan="2">Logically same as in BEB but avoids selection of earlier slots only up to ($W_i/2-1-j$)</td></tr>
<tr><td>Pros and Cons</td><td colspan="2">Pros: Avoids cross collisions
Cons: Increases average backoff delay per retransmission stage from $W_i/2$ to $3W_i/4$</td><td colspan="2">Pros: Reduces average backoff delay for current retransmission stage if j was high in last stage
Cons: Cannot avoid cross collisions</td><td colspan="2">Pros: Avoids cross collision with the least possible increase in the average backoff delay per retransmission stage</td></tr>
</table>

Performance summary	Increases network throughput with delay penalty	Decreases network throughput while delay performance is almost same as in BEB	Increases network throughput with reduced packet delay; balanced throughput-delay gain

3. Reactive Backoff Algorithm

The proposed reactive backoff algorithm is built on top of the BEB scheme. Hence, we first explain the pure BEB scheme. Then, we explain the cross collision problem. After that we elaborate the collision exclusion feature of the proposed reactive backoff scheme.

3.1. Pure BEB

The BEB updates its contention window for each contention stage $i \in [1, 2, \ldots, R]$, where R is the maximum allowed retry limit, based on the failure or the success of the previous access attempt. At the initial transmission attempt $(i = 0)$ of a packet, it randomly selects an equi-probable slot within $[0, W_0 - 1]$, where W_0 is the minimum contention window. Whenever a collision is experienced, re-access would be arranged in the expanded contention window $[0, \min\{(2^i \times W_0 - 1), W_{\max}\}]$ where $W_{\max} = (2^R \times W_0 - 1)$. A STA resets its contention window to the specified minimum W_0 after a successful transmission, or when the number of transmission attempts for the packet reaches R.

3.2. Cross Collision in Pure BEB

Let us assume that a group of STAs which are in their ***i***-th contention stage want to access the channel at a time. Let us further assume that $x \geq 2$ number of STAs from the group select the same contention slot j_x within the window $[0, W_i - 1]$, and the rest y STAs select their contention slots larger than j_x. In such scenario, collision occurs at j_x. After EIFS the collided x STAs double their contention window to $[0, W_{i+1} - 1]$ and randomly select any of the slot in the expanded window for their next access. Note that some part of the expanded contention window of the x STAs, $[0, (W_{i+1}/2 - 1 - j_x)]$, is overlapped with the contention window of the y STAs. Hence, if x STAs select any of the slots from the overlapped portion, it is more likely that they collide with any of the y STAs; the y STAs already have picked up the slots in that portion before the x STAs have initiated their (i+*1*)-th contention resolution round. This type of collision between the STAs in different contention stages, for e.g. x STAs are in their (i+*1*)-th stage while y STAs are still in their ***i***-th stage, is defined as cross collision in [19]. In [19], the probability of such cross collision between the STAs in different contention stages, $\Pr_{xc}(j)$, is obtained to be

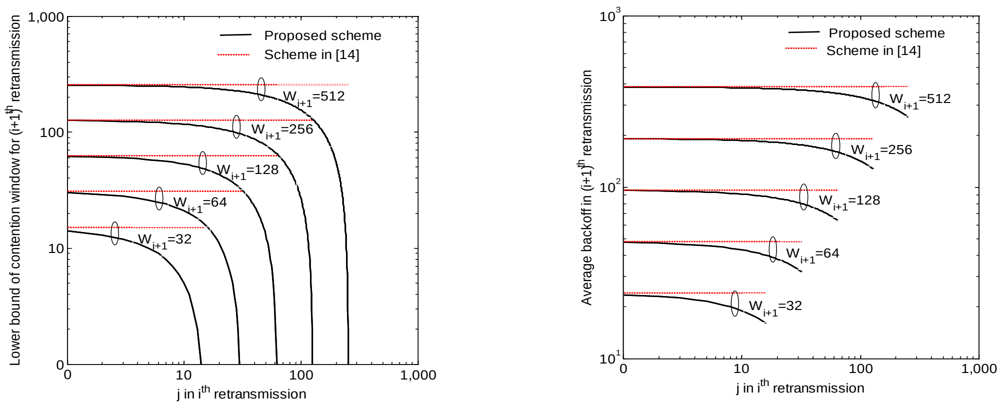
$$\Pr_{xc}(j) = \frac{(2^i W_0 - j)^2}{2^{2i+1} W_0^2}. \tag{1}$$

It is obvious that the cross collision probability depends on j. In the worst case, when j is *0*, $\Pr_{xc}$ is ½. If the cross collision chances between non adjacent contention stages are also considered, it asymptotically rises to 1. Hence, the cross collision should be avoided to reduce overall collision probability in the channel. In the following subsection, we present a scheme which deterministically eliminates cross collisions. In [20], the authors have presented a probabilistic scheme to avoid cross collisions. There is a fundamental difference in the operational mechanism between the scheme presented in this paper and the scheme presented in [20]. In [20], a dynamically-changing non-uniform Probability Distribution Function (PDF) over the expanded contention window is designed where shape of the distribution curve is automatically controlled using the selected j in the previous contention stage. Differently from [20], the scheme presented in this paper logically updates the lower bound of the expanded contention window to a value sufficiently enough to exclude the collision prone contention slots from the contention window. In the next sub-section we describe the proposed scheme in detail.

3.3. Reactive BEB

The contention window expansion/reset procedure of the proposed reactive backoff algorithm is exactly same as in BEB. However, there is a slight difference in the contention slot selection process. For selecting a contention slot from the contention window, a conditional clause that we have appended should be met first. The fulfillment of the clause, during the slot selection process, guarantees the avoidance of the prospective cross collisions.

Every STA that experiences collision determines the overlapped contention slots between the adjacent contention stages based on its backoff history of the previous contention stage that ended in a collision. For example, if a STA that is in its *i*-th contention stage experiences a collision, while contending by selecting the contention slot $j \in [0, W_i - 1]$, the overlapped portion of the contention window in (*i+1*)-th stage would be $[0, (W_{i+1}/2 - 1 - j)]$. Once the overlapped contnetion slots have been noticed, the collided STA simply checks whether a randomly chosen slot in the expanded window is beyond $(W_{i+1}/2 - 1 - j)$ or not. If the randomly selected slot is beyond the aforementioned overlap bound, the slot is used for the next contention. Otherwise, the random selection is repeated until the above mentioned clause is satisfied. It is logically equivalent to the action of updating the lower bound of the contention window to $(W_{i+1}/2 - 1 - j)$ and selecting the contention slot in the interval $[(W_{i+1}/2 - 1 - j), W_{i+1} - 1]$. **Fig. 1-(a)** depicts the change in the logical lower bound of the contention window with respect to j.



(a) **(b)**

Fig. 1. Effect of j in *i*-th retransmission on the: (a) lower bound of contention window for (*i+1*)-th retransmission, and (b) average backoff delay in (*i+1*)-th retransmission

We have noticed a scheme in [16] which can also avoid cross collisions. In that scheme, upon *i*-th collision lower bound of the contention window is updated to the $(W_{i+1}/2-1)$. Despite the fact that it can well avoid cross collisions, it incurs larger average backoff delay per retransmission stage (in comparision to the BEB). Especially in the situations when j is high, the increase in the average backoff delay is a nuisance. On the other hand, our scheme reacts according to j and updates the bound in such a way that cross collision is excluded with the least possible increase in the average backoff delay. **Fig. 1-(b)** depicts the average backoff delay per retransmission for the scheme in [16] and the proposed scheme. It is worth mentioning that the apparent wastage of the channel resources due to the slightly elongated average backoff delay will be easily compensated by the saving in the channel time that could have been wasted due to the cross collisions.

The proposed scheme can be integrated with some other schemes to further enhance the performance of the heavily loaded networks. For example, we can use the proposed scheme in Gentle Decrease in [10] and Slow Decrease in [11]. They are different from the BEB in the way that they reset their contention window after each successful packet transmission. They reset the window to some other suitable window (not to the specified minimum contention window as in BEB); while they expand the contention window upon collision as in the legacy BEB. The contention window expansion function in these algorithms can be replaced with the proposed scheme. As such, the combination of the 'reactive contention window update' upon collision and 'slow/gentle contention window decrease' upon success would further increase the performance of the heavily loaded network.

In the next section we present the performance evaluation framework of the proposed scheme for the DCF based IEEE 802.11b WLAN. Note that the proposed scheme can be used in Enhanced Distributed Channel Access (EDCA) based IEEE 802.11e WLAN as well. The EDCA is fundamentally different than the DCF in the aspect of providing Quality of Service (QoS). It supports Quality of Service (QoS) differentiated four Access Categories (ACs): AC_Voice, AC_Video, AC_Best Effort, and AC_Background. Differentiation is achieved by specifying different contention parameters, like Arbitration Inter Frame Space (AIFS) and minimum/maximum contention window size for the different ACs. For higher priority ACs, smaller contention parameters are specified. No matter which AC they belong to, all the STAs access the channel in the same way but with different contention parameters. Hence, the proposed backoff scheme is applicable to the EDCA as well. The proposed scheme, if used in the EDCA, contributes in enhancing the per AC throughput.

4. Numerical Performance Evaluation Framework

The carried numerical analysis follows a modular approach. Firstly, we study the behavior of a single tagged STA by formulating a single dimensional Markov chain as in [21]. By solving the chain, we obtain the probability $\tau = P(TX)$ that a STA transmits in a randomly chosen slot. Secondly, we formulate equations of the channel throughput and packet delay as a function of τ for the two access schemes, the basic one and the RTS/CTS, respectively. We made following assumptions for the analysis: (a) there are finite number of STAs in the network, (b) all the STAs always have packets to transmit, and (c) the channel is ideal. We present the mathematical foundation presented in [21] so that it will be easy to understand the difference between the proposed scheme and the original scheme.

4.1 Analytical Model

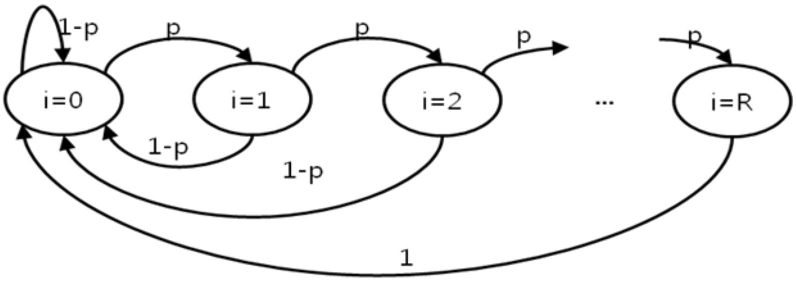


Fig. 2. Stage transition diagram of a tagged STA

A Markov chain for a tagged STA is presented in **Fig. 2**. In the chain, let $s(k)$ be the stochastic process representing the contention stages of the tagged STA at slot time k. The key approximation in this model is that the probability p that a transmitted packet collides is independent of the state $s(k)$. The only non-null one step transition probabilities of the chain are as follows

$$\begin{aligned} P(i\,|\,i-1) &= p \qquad && i = 1, 2, \ldots, R, \\ P(0\,|\,i) &= 1-p \qquad && i = 0, 1, \ldots, R-1, \\ P(0\,|\,R) &= 1 \qquad && i = R. \end{aligned} \tag{2}$$

A transition probability matrix T of dimension $(R+1)\times(R+1)$ can be generated from (2). From T, the steady state probability distribution $\Re$ can be obtained by solving the following equation

$$\Re = \Re \cdot \mathrm{T}. \tag{3}$$

The $\Re$ can simply be interpreted as the conditional probability $P(s=i\,|\,TX)$ for $i \in (0,1,\ldots,R)$ when a STA being transmitting (TX) is found in stage i. This can simply be obtained by solving (3) and can be expressed as

$$P(s=i\,|\,TX) = \frac{(1-p)p^{i}}{1-p^{R+1}} \qquad i \in (0,1,\ldots,R). \tag{4}$$

The probability that the tagged STA transmits while being in backoff stage i, $P(TX\,|\,s=i)$ is

$$P(TX\,|\,s=i) = \frac{1}{1+E[b_i]}, \tag{5}$$

where $E[b_i]$ is the average backoff counter in number of slots extracted by the tagged STA entering the stage i. With the information of conditional transmission probabilities in (4) and (5), $P(TX)$ can be obtained using superposition and Bayes' theorem,

$$P(TX)\sum_{i=0}^{R}\frac{P(s=i\,|\,TX)}{P(TX\,|\,s=i)} = \sum_{i=0}^{R} P(s=i) = 1, \tag{6}$$

where $P(s=i)$ denotes the probability of an event that the tagged STA is found in the backoff stage i. Plugging (4) and (5) in (6) with additional simplification, it is reduced to

$$P(TX)=\tau=\frac{1}{1+\frac{1-p}{1-p^{R+1}}\sum_{i=0}^{R}p^{i}E[b_i]}. \tag{7}$$

$E[b_i]$ for BEB is always $\frac{W_i}{2}$ for $0\le i\le R$. Since the overlapped slots in contention stages $i\ge 1$ are restricted to be selected in the proposed scheme, $E[b_i]$ is changed to the following relation

$$E[b_i]=\frac{2}{W_i}\sum_{j=0}^{W_i/2}\left(j+\frac{W_i-j}{2}\right). \tag{8}$$

Plugging (8) in (7), τ for the proposed scheme can be obtained, which is given by the following equation

$$\tau=\frac{1}{1+\frac{1-p}{1-p^{R+1}}\frac{2}{W_0}\sum_{i=0}^{R}\left(\frac{p}{2}\right)^{i}\sum_{j=0}^{W_i/2}\left(j+\frac{2^{i}W_0-j}{2}\right)}. \tag{9}$$

In the steady state with stationary channel, the tagged STA transmits a packet with probability τ, so that the conditional collision probability can be expressed as

$$p=1-(1-\tau)^{n-1}. \tag{10}$$

Equations (9) and (10) represent a pair of nonlinear equations with two unknowns τ and p, which can be solved using numerical methods to get a unique solution. In the next subsection, we present the performance metrics which are obtained as a function of τ and p.

4.2 Performance Metrics

We present the definition of the two performance metrics that we consider in this paper.

A. Normalized Throughput

Normalized system throughput S is the fraction of time that the channel is used for transmitting payload bits successfully. As in [22], it can be expressed as

$$S=\frac{E[\,payload\ \ size\ in\ a\ slot\ time]}{E[length\ of\ \ a\ slot\ time]}. \tag{11}$$

Let P_{tr} be the probability that there is at least one transmission in the considered slot time and P_s be the probability that the transmission is successful, thus we have

$$P_{tr} = 1-(1-\tau)^n , \tag{12}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} . \tag{13}$$

With reference to (12) and (13), (11) can be restated as

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})T_i + P_s P_{tr} T_s + (1-P_s)P_{tr}T_c} , \tag{14}$$

where T_s and T_c are the average time the channel is sensed busy because of successful transmission or collision, respectively. $E[P]$ is the average packet length. T_i is the duration of a slot time subject to the physical layer techniques, e.g., $20\mu s$ for DSSS in [2]. We denote the packet header as $H = PHY_{hdr} + MAC_{hdr}$. Consequently, T_s and T_c for the basic access method can be expressed as

$$\begin{aligned} T_s^{bas} &= H + E[P] + SIFS + ACK + DIFS , \\ T_c^{bas} &= H + E[P] + DIFS , \end{aligned} \tag{15}$$

where $E[P]$ is the average payload size. Similarly, T_s and T_c for the RTS/CTS mechanism can be expressed as

$$\begin{aligned} T_s^{rts} &= RTS + 3SIFS + CTS + H + E[P] + ACK + DIFS , \\ T_c^{rts} &= DIFS + RTS . \end{aligned} \tag{16}$$

Please note that the propagation delay is not included in the analysis.

B. Average Packet Delay

Average packet delay, D, is the time duration from the moment that the packet is at the head of its MAC queue ready to be transmitted, to the moment an acknowledgement (ACK) for this packet is received at the sender side. If the packet is dropped upon reaching specified maximum retransmission limit, this delay will not be included into the calculation. D is derived in [21] which is as follows

$$D = \frac{n}{S/E[P]} - E[slot](1-B_0)\frac{p^{R+1}}{1-p^{R+1}}\sum_{i=0}^{R}(1+E[b_i]) , \tag{17}$$

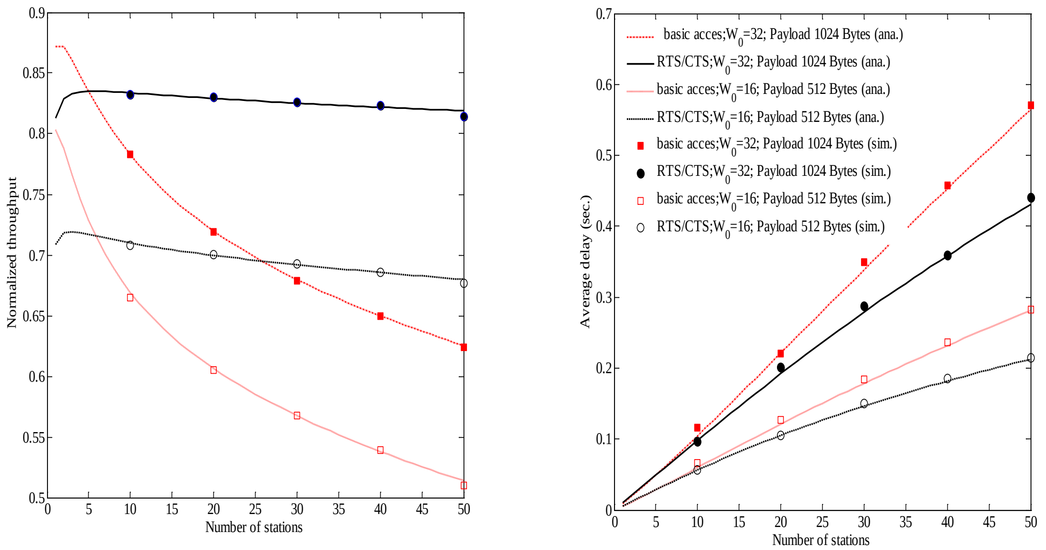
where, $E[slot]$ is equal to the denominator in (14) and $B_0 = \frac{1}{(W_0+1)}$.

5. Model Validation and Performance Evaluation

In this section, we first validate the accuracy of the developed analytical model through simulation experiments and then use the model to evaluate and compare the performance of the proposed scheme with the other schemes: BEB in [2], XCE_A in [16], and UBB in [17].

5.1 Model Validation

The adequate accuracy of the model is verified by comparing the analytical results with those obtained from simulation experiments carried in ns-2 [23]. We simulate an uplink packet transmission scenario in a typical Infrastructure Basic Service Set (IBSS) where an Access Point (AP) is loacated at the centere of a network area (50m*50m) and *n* stationary STAs are uniformly distributed in the newtwork area. We consider the MAC and the PHY parameters as specified in IEEE 802.11b specificaions which are summarized in **Table 2**. All the STAs transmit UDP packets of same size to the AP. The packet sending rate of each station is kept sufficiently high such that the MAC queue never remains empty. No Ad-Hoc Routing Agent (NOAH) [24] is used to bypass the effect of routing in the network's performance.



(a) **(b)**

Fig. 3. Model validation via comparing analytical and simulation results: **(a)** saturation throughput, and **(b)** average packet delay. Legends are common for both of the above figures.

Fig. 3 shows that the analytical model predicts normalized throughput and average packet delay with adequate accuracy: analytical results (lines) matches well with the simulation results (markers), in both the basic and the RTS/CTS access mechanisms for different configuration of W_0 and payload sizes for varying number of contending stations. Each presented simulated results are the average of the 30 iterations in simulation. Having validated the accuracy of the model, our next persuit is to use the model to evaluate the performance of the proposed scheme in different network settings and compare it with the other schemes.

5.2 Performance Evaluation and Comparison

We compare the performances of the proposed scheme, based on our validated analytical model considering the IEEE 802.11b system parameters tabulated in **Table 2**, with the three other schemes: BEB in [2], XCEA in [16], and UBB in [17].

Table 2. Parameters considered in the analysis

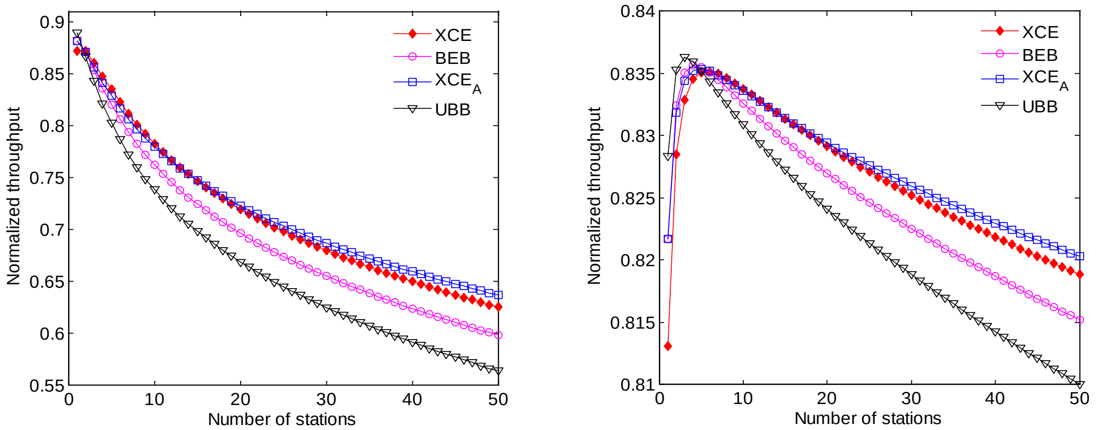
Parameters	**Values**
Slot time	20 μs
MAC header	224 bits
PHY header	192 bits
RTS packet	160 bits + PHY header
CTS packet	112+ PHY header
ACK packet	112 bits + PHY header
DIFS	50 μs
SIFS	10 μs
Channel data rate	1 Mbps
Control data rate	1Mbps
Minimum contention window size	32
Maximum contention window size	1024
Retransmission limit	6

There are two major factors that deteriorate the throughput and the delay performances of the network: time spent in collisions and following retransmissions to resolve them; and backoff delay before data transmissions. The proposed backoff scheme has been found to have the best tradeoff between these two factors and thus offers the balanced throughput-delay gain. **Fig. 4** and **Fig. 5** depict the throughput and delay performances of all the considered schemes. XCE_A yields the highest throughput for both the basic and the RTS/CTS access mechanism. However, it enhances the throughput performance at the expense of increased average packet delay as we can be observed in **Fig. 5**. Especially when the network is heavily loaded, XCE_A significantly increases the average packet delay. On the other hand, the proposed XCE nearly attains the throughput gain as XCE_A does with significantly reduced delay as shown in **Fig. 5**. For example, in the basic access mechanism, the proposed scheme attains almost similar throughput as in XCE_A with approximately 20 *ms* less delay when the number of STAs are 50. In general, the throughput-delay performance of the considered schemes can be characterized with inequality relation $S_{XCE_A} > S_{XCE} > S_{BEB}$ and $D_{XCE} < D_{BEB} < D_{XCE_A}$ for all n where S_z and D_z are respective throughput and delay of the scheme Z. Therefore, the proposed XCE has the best tradeoff and hence offers a well balanced throughput-delay gain.

To better explain the previous throughput and delay performances, we analyze the following four measures

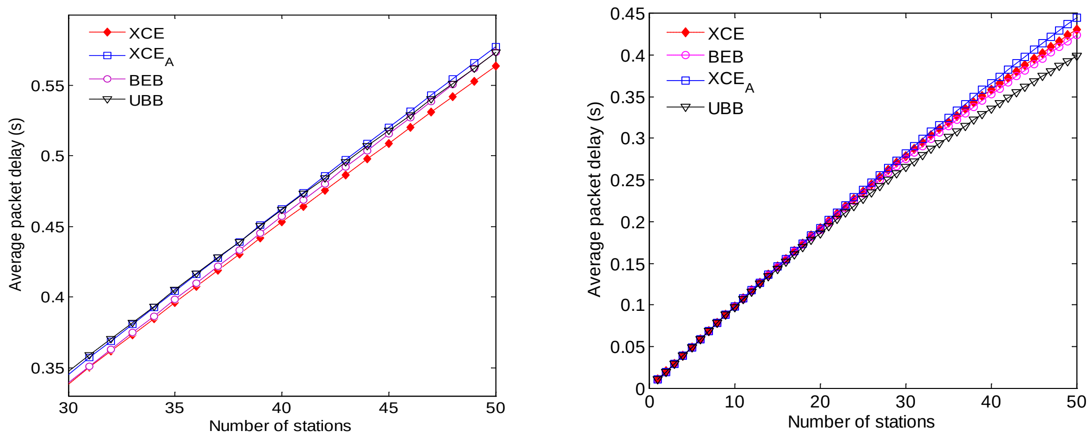
i) The *average number of idle slots per successful packet transmission*, which can be obtained as $(1-P_{tr})/(P_{tr}\cdot P_s)$

ii) The *average channel time wasted in collisions per successful packet transmission*, which can be obtained as $\left(\frac{1}{P_s}-1\right)\cdot T_c$



(a) Basic access mechanism **(b)** RTS/CTS access mechanism

Fig. 4. Normalized throughput comparison for different schemes



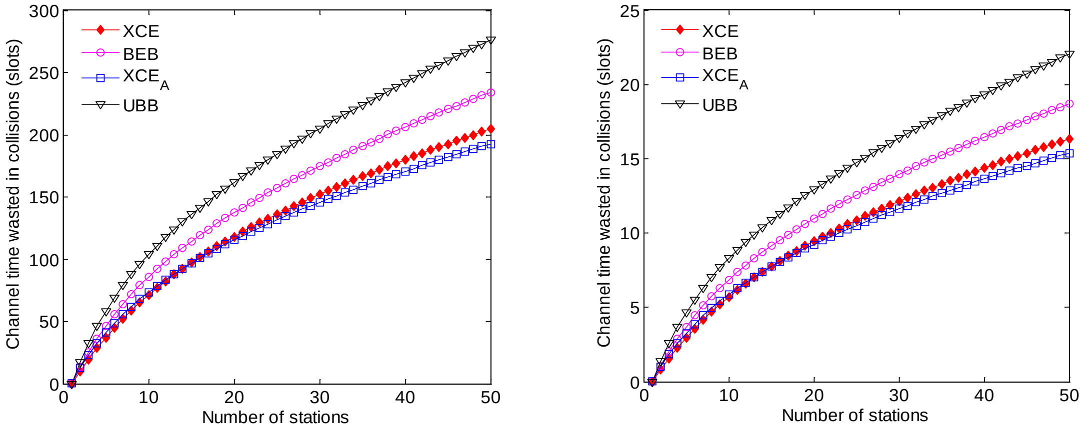
(a) Basic access mechanism **(b)** RTS/CTS access mechanism

Fig. 5. Average packet delay comparison for different schemes

iii) The *average number of retransmissions per packet*, which can be obtained as $1/(1-p)$, and

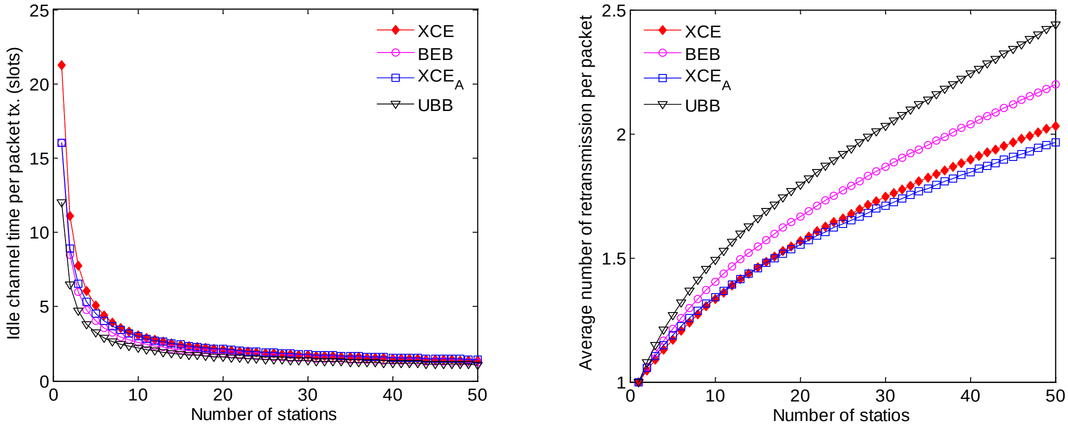
iv) The *average backoff duration* in each retransmission

Even though the average backoff durations of the XCE and the XCE$_A$ in each retransmission stages (except for $i=0$) are larger than that of the BEB and the UBB, they maintain the average idle slot time per successful transmission almost equal as in the BEB and the UBB (see **Fig. 7-(a)**). Beside that, the XCE and the XCE$_A$ achieve significant reduction in the wastage of the channel time due to collision as can be noted in **Fig. 6**. As the consequence



(a) Basic access mechanism **(b)** RTS/CTS access mechanism

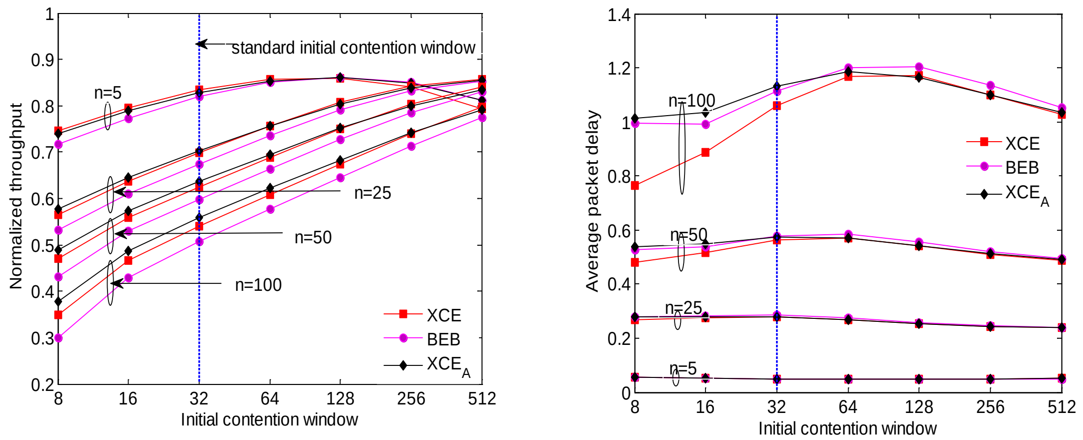
Fig. 6. Overheads in terms of channel time wasted in collisions per successful packet transmission



(a) Idle channel time **(b)** Average retransmissions

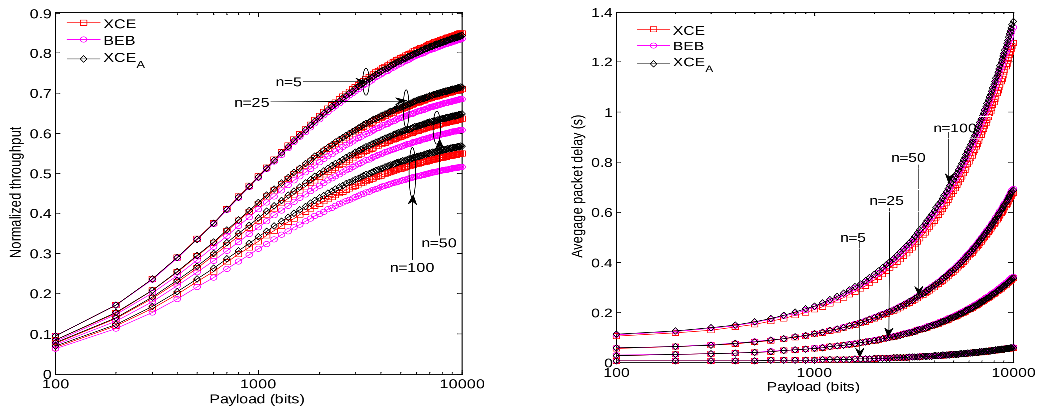
Fig. 7. Overheads in terms of idle channel time and average number of retransmissions per successful packet transmission for both the basic and RTS/CTS access mechanism

of significant collision reduction, the XCE and the XCE$_A$ further reduce average number of retransmissions for the successful packet transmission as presented in **Fig. 7-(b)**. It is noteworthy to mention that the XCE minimizes the performance degrading factors (such as idle slots per successful packet transmission, channel time wasted due to packet collision per successful transmission, and number of retransmission per successful packet transmission) as efficiently as the XCE$_A$ does but with a big advantage of reduced average backoff time per retransmission (due to reactive lower bound update according to j as can be noticed in **Fig.1**). Therefore, the XCE achieves balanced throughput-delay gain.



(a) Normalized throughput **(b)** Average packet delay

Fig. 8. Normalized throughput-delay (in basic access mechanism) for varying initial contention window sizes



(a) Normalized throughput **(b)** Average packet delay

Fig. 9. Normalized throughput-delay (in basic access mechanism) for varying payload sizes

To verify the consistency of the balanced throughput-delay gain of the proposed scheme over the different system and application parameters, we present the throughput-delay performance for a wide range of initial contention window and packet length values. Throughput gain for the XCE and the XCE_A in **Fig. 8-(a)** is observed to be even higher when the initial contention windows are smaller than the standardized initial contention window in IEEE 802.11b (marked with vertical dotted line in the figure) for every n. The amount of gain, however, starts to diminish for the higher values of initial contention window, but still maintains some positive gain throughout. Among the throughput gain of the XCE and the XCE_A over the legacy BEB, the gain of the latter one seems higher. However, it suffers from the negative delay gain, i.e., it increases delay especially for the cases when the initial contention windows are small and n is large, as can be seen in **Fig. 8-(b)**. Unlike the XCE_A, the XCE offers throughput gain with reduced packet delay; the reduction in delay by XCE is even higher for smaller values of initial contention windows. Throughput-delay performance presented in **Fig. 4** and **Fig. 5** are for the case when the packet size is 1024 *bytes*. Hence, in **Fig. 9** we present a result to explain how well the XCE maintains its balanced throughput-delay gain over varying packet sizes, ranging from 100 to 10,000 *bytes*. From the figure one can see that the larger the packet size is, the larger would be the throughput-delay gain. It is more interesting to note that, for both the XCE and the XCE_A, even for the smaller packet sizes the throughput gain is still efficient if there is large network population. Likewise in the previous results with the fixed packet size, in this case also the XCE has the delay advantage over the $XCE_{A.}$

6. Conclusions

The performance of a random access network strongly depends on the collision resolution efficiency of the underlying MAC protocol. To enhance the collision resolution efficiency of a popular CRA that has been used in the MAC of the 802.11 based WLAN, we proposed a reactive algorithm. The proposed reactive algorithm contributes to significant performance improvements in the network since it offers a supplementary feature of Cross Collision Exclusion (XCE) while retaining the legacy collision mitigation features.

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Subodh Pudasaini received B.E. degree in Electrical and Electronics Engineering from Kathmandu University, Nepal, in 2005, and M.E degree in Computer Engineering from Chosun University, Korea, in 2008. Currently, he is a Ph.D. student. He is interested in design, analysis and enhancement of architectures, protocols, and algorithms for wireless networks, in particular for WLAN, MAN and PAN. He is a Student Member of the IEEE.

Yusun Chang received M.S. in Electrical Engineering at Columbia University in 2002 and Ph.D. from the Electrical and Computer Engineering at the Georgia Institute of Technology in 2007. Currently, he is an assistant professor in Division of Engineering at Southern Polytechnic State University and an active research member of Communications Systems Center at the Georgia Institute of Technology. In 1996, he instructed air force officers in the Air Force Artillery School for three years in Korea, and worked at Bell Labs in summer 2002. He is also the author of the book, *Robust Mobile Networking.* His research interest includes the modeling and the optimization of wireless mobile networks with an emphasis on the implementation of wireless communication systems for Wireless Multimedia Communications, Vehicular Ad Hoc Networks, and Intelligent Transportation Systems.

Seokjoo Shin received B.E. degree in avionics engineering from Korea Aerospace University, Korea in 1997, and M.S. and Ph.D. degrees in information and communications from Gwangju Institute of Science and Technology (GIST), Korea, in 1999 and 2002, respectively. He joined the Mobile Telecommunication Research Laboratory, Electronics and Telecommunications Research Institute (ETRI), Korea, in 2002. In 2003, he joined the Faculty of Engineering, Chosun University, where he is currently an Associate Professor in the Department of Computer Engineering. He spent 2009 as a Visiting Researcher at Georgia Tech, USA. His research interests include 4G Networks, MIMO-MAC techniques, Underwater Communications, and WSN.