EBA: An Enhancement of IEEE 802.11 DCF via Distributed Reservation

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Abstract—The IEEE 802.11 standard for Wireless Local Area Networks (WLANs) employs a Medium Access Control (MAC), called Distributed Coordination Function (DCF), which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The collision avoidance mechanism utilizes the random backoff prior to each frame transmission attempt. The random nature of the backoff reduces the collision probability, but cannot completely eliminate collisions. It is known that the throughput performance of the 802.11 WLAN is significantly compromised as the number of stations increases. In this paper, we propose a novel distributed reservation-based MAC protocol, called Early Backoff Announcement (EBA), which is backward compatible with the legacy DCF. Under EBA, a station announces its future backoff information in terms of the number of backoff slots via the MAC header of its frame being transmitted. All the stations receiving the information avoid collisions by excluding the same backoff duration when selecting their future backoff value. Through extensive simulations, EBA is found to achieve significant increase in the throughput performance as well as a higher degree of fairness compared to the 802.11 DCF.

Index Terms—IEEE 802.11, distributed reservation, WLAN, EBA, collision avoidance, piggyback, throughput.

1 INTRODUCTION

The increased mobility as a common trend in today’s business has lead to the prominent technology of wireless communications. As a result, wireless local area network (WLAN) is emerging as a dominant means of wireless communications and the Internet access. IEEE 802.11 is the most popular WLAN technology, which supports high-speed communications up to 54 Mbps in the unlicensed bands such as those in 2.4 GHz and 5 GHz [1][12].

The IEEE 802.11 standard specifies two Medium Access Control (MAC) schemes, namely, a mandatory Distributed Coordination Function (DCF), and an optional Point Coordination Function (PCF) [1]. Most of today’s WLAN devices implement DCF only due to its simplicity and the efficient best-effort service provisioning.
DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA), in which a station transmits its frame only if the medium is determined to be empty, i.e., not occupied by other station(s). The collision avoidance mechanism utilizes the random backoff prior to each frame transmission attempt. While the random backoff can reduce the collision probability, it cannot completely eliminate the collisions since two or more stations can finish their backoff procedures simultaneously.

As the number of contending stations increases, the number of collisions is also likely to increase. The DCF implements a binary exponential backoff by increasing the contention window size (which determines the maximum backoff duration) exponentially for each transmission failure in order to reduce consecutive collisions. However, in certain situations, this exponential backoff results in a channel idling such that the channel is not efficiently utilized. Due to all these facts, it is well known that the throughput performance is severely compromised as the number of contending stations increases [10]. The performance degradation due to the collisions becomes more severe as the frame size increases since the bandwidth waste by collisions becomes relatively large. Moreover, retransmissions due to collisions consume the precious communication energy, thus reducing the lifetime of battery-powered wireless devices.

A well-designed MAC protocol should provide simplicity, fairness, and also high throughput. In general, MAC protocols for WLANs can be categorized into two classes: contention-based MAC and reservation-based MAC protocols [5]. The contention-based MAC protocols, e.g., the 802.11 DCF and those found in [2][3], are generally distributed protocols where each station decides when to transmit based on its own decision. On the other hand, reservation-based MAC protocols, e.g., the 802.11 PCF, are usually centralized protocols in which a centralized coor-
dinator, e.g., the access point (AP) in the typical WLAN, reserves the medium and allocate the bandwidth for each station’s transmission. Typically, the distributed MAC is more suitable than the centralized MAC when the number of stations is small and vice versa. Meanwhile, the distributed MAC is often preferred due to simplicity.

In this paper, we propose a novel distributed reservation-based MAC protocol by enhancing the legacy 802.11 DCF. Our design is motivated by the fact that under DCF, collisions happen since stations are not aware of when others will start their transmissions. The start of a frame transmission is determined by each station’s backoff duration. If stations knew the backoff durations of other stations, they could set their backoff duration so as not to conflict with each other, which in turn will prevent collisions. We use this simple intuition. The proposed distributed reservation-based MAC protocol is called Early Backoff Announcement (EBA). By adding their backoff value information into the MAC header of each transmitted data frame, stations exchange their future backoff duration information, and hence use it to completely eliminate collisions. A key advantage of EBA is its backward compatibility with the legacy 802.11 DCF such that the 802.11 DCF stations and EBA stations can co-exist smoothly even though the throughput performance should be compromised in such situations. Knowing that the 802.11 WLAN is widely deployed in the real world already, the backward compatibility is considered a very important requirement for any new MAC protocol for WLANs.

The rest of this paper is organized as follows. In Section II, we briefly introduce the IEEE 802.11 DCF protocol, which is the basis of the proposed MAC. Section III presents our proposed distributed reservation-based MAC protocol, EBA (Early Backoff Announcement). We compare the 802.11 DCF with EBA through simula-
tions in Section IV. Finally, we conclude our paper in Section V.

2 PRELIMINARIES

2.1 IEEE 802.11 Distributed Coordination Function (DCF)

IEEE 802.11 specifies two different MAC schemes: the mandatory DCF and the optional PCF [1]. Today, most 802.11 WLAN devices implement the DCF only due to its simplicity. The DCF is based on CSMA/CA, and it only provides asynchronous access for the best effort service.

The basic operation of the DCF is illustrated in Fig. 1. If a station generates a frame to transmit when there is no on-going backoff procedure, it checks the medium status to see if it is idle. If the medium is sensed to be idle, the station immediately proceed with its transmission after an idle interval equal to DCF Inter Frame Space (DIFS); this is often referred to as an immediate access. If the medium is sensed to be busy, the station defers its access until the medium is determined to be idle for a DIFS interval, and then it starts a backoff procedure.

A backoff procedure starts by setting its own backoff timer by uniformly choosing a random value from the range \([0, \text{CW}]\), where, \(\text{CW}\) is the current contention window size, and its size is an integer value within the range of \(\text{CW}_{\text{min}}\) and \(\text{CW}_{\text{max}}\). The backoff counter is decreased by a slot time (aSlotTime) as long as the channel

Fig. 1. Basic access mechanism in DCF.
is sensed idle, while it is frozen when the channel is sensed busy. The backoff counter count-down is resumed after the channel is sensed idle for a DIFS interval. When the backoff counter reaches zero, the station starts its data frame transmission. If the source successfully receives an acknowledgement (ACK) frame after a Short Inter-Frame Space (SIFS) idle period, the transmission is assumed to be successful.

After a successful transmission, the source resets its contention window to the minimum value $CW_{\text{min}}$, and performs another backoff process irrespective of whether it has another frame to transmit or not. This process is often referred to as post backoff, and it prevents a station from performing consecutive immediate accesses. On the other hand, if a frame transmission fails, the current contention window size is doubled with the maximum value $CW_{\text{max}}$. The station attempts to transmit the frame again by selecting a backoff counter value from the increase contention window. After the number of failures reaches a retry limit, which is 4 by default, the station drops the frame.

2.2 Related Work

There have been remarkable studies on IEEE 802.11 MAC protocol to improve system throughput or support differentiated services. The modeling of IEEE 802.11 DCF has been a research focus since the standard has been proposed. The analysis model proposed in [10] simplifies the backoff behavior of 802.11 DCF by using a discrete Markov chain. Using the model, the author of [10] demonstrates that the performance of DCF strongly depends on the system parameters, mainly, the minimum contention window and the number of stations. It motivates a significant amount of subsequent analysis work. Cali et al. [17] derive a theoretical upper bound by approximating DCF with a $p$-persistent protocol. They also propose a dynamic and distributed algorithm, IEEE 802.11+, which allows each station to es-
imate the number of competing stations and to tune its contention window to the optimal value at run time. H. Kim et al. [21] have derived an analytic model and developed a model-based frame scheduling scheme, called MFS, to enhance the capacity of IEEE 802.11 WLANs. In MFS, each station estimates the current network status and utilization, and then based on the estimation, it determines a scheduling delay that is introduced before a station attempts for transmission of its pending frame.

Several recent proposals [5], [19] improve the throughput of DCF by either modifying the backoff mechanism or tuning the various inter-frame spacing time. The Fast collision resolution (FCR) is a new contention-based MAC protocol [5]. It actively redistributes the backoff timer for all competing nodes, thus allowing more recent successful stations to use smaller contention window, and allowing other stations to reduce back-off timer exponentially when they continuously meet some idle time slots. Due to this operation, each station can more quickly resolve collisions and obtain higher throughput than DCF when there are a large number of active stations. DCF+, proposed in [19], is a new ACK-integrated mechanism that combines the TCP ACK with MAC-level ACK, and enhances the performance of TCP over WLANs.

Several schemes that dynamically alter the value of CW have been proposed and can be found in [11][17][18]. Bianchi and Tinnirello [11] show that the number $n$ of competing stations can be expressed as a function of the collision probability encountered on the channel, and hence it can be estimated based on run-time measurements, and propose a methodology to estimate the number of competing stations, based on an extended Kalman filter coupled with a change detection mechanism.

The authors of [22] propose a distributed MAC scheme, called Blackburst, with
the main goal of minimizing delay for real-time traffic. With this scheme, real-time stations contend for access to the channel in a distributed manner by sending a black burst signal with a duration proportional to the time the station has been waiting. After transmitting the black burst, the station listens to the medium for a short period of time, and transmits its pending frame only if the medium is idle. This scheme basically ensures that the longest-waited station transmits a frame without collision.

Piggybacking mechanisms are used in many systems to support various purposes. For example, in [20], when a base-station sends a packet to a mobile station, the base-station’s scheduler piggybacks the information about the eligible time for the next packet to be transmitted. The enhanced collision avoidance algorithm proposed in [18] – similar to ours – applies piggybacking mechanism to the backoff scheme of DCF. The algorithm involves advertising the transmitting station’s next backoff value and tracking the backoff values of other stations in the network. It also employs a dynamic value for CW based on the result obtained by tracking the number of unique station addresses that have transmitted over the last few seconds. We refer to this piggyback scheme as the basic algorithm as presented in Section 3.1. However, [18] gives only a rough description about the algorithm without considering how it works and performs in various situations such as the existence of newly-arriving stations and power-saving stations. In this paper, we propose enhanced algorithms to reduce the collision probability and improve the system performance as elaborated in Section 3.2.

3 Early Backoff Announcement (EBA)

3.1 Basic Idea
The basic access mechanisms of DCF and EBA are illustrated in Fig. 2. Under DCF, a station performing a backoff procedure starts transmitting a frame when its backoff timer reaches zero. After a successful transmission of the frame, the station resets its contention window size \( CW \) to \( CW_{\text{min}} \), and determines the next backoff period \( b_{\text{next}} \) randomly at the end of the corresponding ACK frame reception, marked as point (1) in Fig. 2 (a), and performs another backoff procedure immediately, even if there is no additional transmissions are currently queued, i.e., a post backoff, as explained in Section II. Our key observation is that next backoff period \( b_{\text{next}} \) could be determined earlier, i.e., point (2) in Fig. 2, without affecting any other MAC procedure negatively. This is because the backoff value is selected randomly.

Under EBA, a station determines its next backoff period not after receiving the ACK, corresponding to point (1) in Fig. 2 (a), but before transmitting the frame, corresponding to point (2) in Fig. 2 (b), and piggybacks this future backoff information into the MAC frame header. For the rest of this paper, we refer to this information as \textit{EBA information}. Due to the broadcasting nature of radio communications, the frame containing the EBA information is announced to all neighbor stations, including the destination. Note that under the DCF, a station is supposed to receive all the incoming frames and at least decode the MAC header part unless it is in the sleeping mode. When the stations receive a frame with the EBA informa-
tion, they are informed when the currently-transmitting station will be transmitting its next frame, and save this information into their Reservation Windows.

The Reservation Window is used to maintain the channel reservation state of the other stations and itself. As shown in Fig. 3, the window is composed of 1024 slots numbered from 0 to 1023. The number 1023 is rooted from $\text{CW}_{\text{max}}$, corresponding to the maximum backoff period of any station. The offset specifies the current slot, and it moves to the right for every aSlotTime during a backoff procedure. When the offset reaches 1023, it wraps around so that the next offset becomes zero. The Reservation Window maintains the following three per-slot variables: $I_{\text{empty}}$, $I_{\text{reserved}}$, and $I_{tx}$, where $I_{\text{empty}}$ is the initial state that does not have any reservation information on the slot, $I_{\text{reserved}}$ denotes that the slot is already reserved by another station, and $I_{tx}$-slot is the transmission slot determined by the backoff period selected by the station itself. (i.e., $I_{tx}$-slot’s number = (offset + backoff) mod $\text{CW}_{\text{max}}$). When a frame is received, the receiving station extracts the reservation information from the MAC header of the received frame, and marks the slot (in the Reservation Window) as $I_{\text{reserved}}$. If the offset meets the slot whose value is $I_{tx}$, the transmission is initiated.

In this manner, each station shares the channel reservation information with other stations. This operation enables a station to reserve the next transmission time with other stations when transmitting a data frame, so that other stations do not reserve and start transmitting a frame on the same slot. Therefore, when a sta-
tion determines its future backoff period, it refers to its Reservation Window and selects a non-reserved time slot to prevent collisions with other stations. Apparently, this operation can eliminate most of the frame collisions.

### 3.2 EBA Algorithms

We use the following notations for the rest of the paper, where $T$ represents the current time:

- $TxQ(Q_{t1}=m, Q_{t2}=n)$ : denotes the state of a station whose $TxQ$ (transmission queue) size is $m$ at slot time $t_1$ and $n$ at slot time $t_2$, respectively.
- $TxQ_{idle,busy}$ station: denotes a station with $TxQ(Q_{t-1}=0, Q_{t}>0)$, i.e., a newly transmitting station.
- $TxQ_{busy,idle}$ station: denotes a station with $TxQ(Q_{t-1}=1, Q_{t}=0)$, i.e., a station that will perform the post backoff procedure.
- $TxQ_{busy,busy}$ (= $TxQ_{busy}$) station: denotes a station with $TxQ(Q_{t-1}>0, Q_{t}>0)$, i.e., a station performing consecutive transmissions.
- $TxQ_{idle,idle}$ (= $TxQ_{idle}$) station: denotes a station with $TxQ(Q_{t-1}=0, Q_{t}=0)$, i.e., an idle station.

The proposed Early Backoff Announcement (EBA) can employ one of two backoff selection algorithms: EBA-1 and EBA-2. Each algorithm has the following characteristics:

1) EBA-1 is a simple MAC with a minor modification of the IEEE 802.11 DCF. It is backward compatible with the legacy DCF. Therefore, EBA-1 and DCF stations can co-exist smoothly in the same WLAN.

2) EBA-2 is the modified version of EBA-1 that has higher throughput than EBA-1 and DCF. It is backward compatible with EBA-1. EBA-1 and EBA-2 stations can co-exist smoothly in the same WLAN.
3.2.1 EBA-1: Backoff Mechanism

Under EBA-1, the operation of selecting the next backoff value is basically equivalent to the backoff selection mechanism of IEEE 802.11 DCF, in which the backoff value $b_{\text{next}}$ corresponding to a non-reserved slot is randomly selected from the range of [0, CW]. The CW value is doubled for every unsuccessful transmission. The difference is that the station selects only non-reserved backoff period using its own Reservation Window, i.e., $I_{\text{empty}}$ slot. After selecting the next backoff period $b_{\text{next}}$, the station piggybacks it into the transmitted frame header (EBA field) and set the $(\text{offset} + b_{\text{next}})$-th slot in the Reservation Window to $I_{\text{tx}}$. When there are more stations than the CW value, it is possible that no empty slots are remaining in 0–CW slots. In such a case, a backoff value is chosen randomly from the non-reserved slots in the range of $[CW, CW + CW_{\text{reserved}}]$, where $CW_{\text{reserved}}$ is the number of reserved slots in its Reservation Windows. For example, let’s consider a station with $CW = 31$. When all slots in the range of [0, CW] in the stations’ Reservation Window are reserved by other stations, and there are 50 ($= CW_{\text{reserved}}$) reserved slots in total in the Reservation Window, this station randomly chooses one of $I_{\text{empty}}$ slots in the range of $[CW, CW + 50]$ ($= [31, 81]$) as the next backoff value because $CW_{\text{reserved}}$ is 50 in this case.

3.2.2 EBA$^1$: Additional Collision Avoidance Operations

A station reserved the channel using EBA can transmit its frame at the reserved time without collision since other stations do not transmit at the time slot. Note that this is a fact only if the reserving station has a frame to transmit at the reserved time slot, i.e., the station is a $T_xQ_{\text{busy,busy}}$ station.

$^1$ When we use the word EBA, we are referring to both EBA-1 and EBA-2
However, the reserving station may not have a frame for the reservation, i.e., a $TxQ_{idle,busy}$ station. In such scenario, the access procedure is the same as that in DCF. $TxQ_{busy,idle}$ stations (performing the post backoff) have no frames to transmit at the reserved slot though they have reserved channel using EBA. Therefore, the channel will stay idle during the slot. Moreover, $TxQ_{busy,idle}$ stations will not be able to reserve the next channel access time because it does not send any reservation information for its next transmission to its neighbors. Let us consider when this sta-

(a) Station X selects 7 as the next backoff value for a newly transmitting frame, and performs the backoff procedure. (Other stations do not know this fact because this is locally executed in station X)

(b) After 1 slot time, a station A starts transmission and reserves the channel by announcing 6 as the next backoff using EBA.

(c) A station X recognizes the conflict and selects neighbor empty-slot to prevent collision.

Fig. 4. Collision Avoidance Mechanism for the non-reserved transmission of $TxQ_{idle,busy}$ Station X
tion attempts to transmit a new frame after such an idling period (correspondent to $TxQ_{idle,busy}$ station). As it did not reserve the channel for its upcoming transmission, other stations do not know the station's backoff value, and hence they can select a backoff value that causes a collision with this station.

We can reduce the collision possibility in such situations by using the additional algorithms as follows.

A. Non-Reserved Transmission of $TxQ_{idle, busy}$ stations

Fig. 4 shows the operation when a $TxQ_{idle, busy}$ station participates in the contention for the medium for a non-reserved transmission. Assume that station X was idle for a while, and now has a new frame to transmit. It sets its backoff counter to 7, and participates in the channel contention. After 1 slot time, $TxQ_{busy,busy}$ station A starts a transmission and reserves its next channel access time by setting its next backoff value to 6. At this time, station X finds that station A is trying to send on the same slot time as it already selected. Because it is impossible to ask station A to change its backoff value, we naturally let the station X be responsible for avoiding the anticipated collision. Therefore, station X alters its current $I_{tx}$-slot into $I_{reserved}$-slot and chooses another $I_{empty}$-slot for its new backoff period (transmission slot).

Here, station X does not select randomly. As shown in Fig. 4 (c), it moves the $I_{tx}$-slot leftwards till it finds an $I_{empty}$-slot, and changes it to the $I_{tx}$-slot. If an $I_{empty}$-slot does not exist on the left side, then it chooses an $I_{empty}$-slot, which is the closest from the original $I_{tx}$-slot, on the right side.
B. Newly Arriving Station

Fig. 5 shows the operation for a situation when a new station joins the WLAN. This situation is similar to the above-considered situation, but is significantly different in the sense that the station has no reservation information of its new neighbors in its Reservation Window. In this case, the station generates a backoff value, and begins the backoff procedure. In Fig. 5, we assume that station Y newly joins and selects the backoff value 2 for its transmission. After 2 slot times, station

<table>
<thead>
<tr>
<th>Station</th>
<th>Offset</th>
<th>Backoff Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station A</td>
<td>i+i+1</td>
<td>3 (slot time)</td>
</tr>
<tr>
<td>Station B</td>
<td>j+i+1</td>
<td>7</td>
</tr>
<tr>
<td>Station Y</td>
<td>k+2</td>
<td>1</td>
</tr>
</tbody>
</table>

(a) The newly arriving station Y selects 1 as its backoff value for its transmission. (Other stations do not know this information.)

(b) After 1 slot time, station Y starts transmission and reserves the channel by announcing 6 as the next backoff using EBA.

(c) Station B recognizes the conflict and selects neighbor empty-slot to prevent collision. Station A also recognizes other station’s conflict and sets its neighbor empty slot to \( I_{reserved} \)-slot.

Fig. 5. Collision Avoidance Mechanism for a newly arriving station
Y starts transmission, and reserves the next channel access time by indicating 7 as the next backoff value in its frame transmitted. This is feasible since station Y did not know that the slot time 7 has been already reserved by station B. After receiving the EBA information, the station B perceives that station Y is planning to transmit on the same time slot. To prevent a collision, similar to the case in Fig.4, station B concedes the reservation to station Y by withdrawing its own reservation and selecting its nearest empty neighbor slot on the left side as a new backoff value. A neighboring station, station A, can also recognize this conflicting situation by checking the duplicate reservation on the X-slot. Using the same algorithm used by station B, station A can also find the new backoff value of the yielding station B, and sets the corresponding slot to an X-slot. In this manner, the collision probability caused by newly arriving stations can be minimized.

3.2.3 Estimate the Number of Contending Stations

Several performance evaluation studies of the IEEE 802.11 DCF show that performance of the DCF is very sensitive to the number of stations competing for the channel [10, 11]. This is in part because $C_{\text{W}_{\text{min}}}$, which is determined depending on the underlying PHY, is too large when the number of stations is small, and vice versa. That is, even when there are only a few “active” stations, i.e., stations that are attempting to transmit, the initial backoff value is still selected from the range of [0, $C_{\text{W}_{\text{min}}}$]. For example, in case of IEEE 802.11b PHY, $C_{\text{W}_{\text{min}}}$ is defined to be 31. Thus, the idle period increases and the channel resources are wasted when there are a few stations. On the other hand, the $C_{\text{W}_{\text{min}}}$ value of 31 can result in frequent collisions when there are a lot of competing stations.
Under EBA, the number of competing stations can be estimated easily by counting the number of reserved slots in the Reservation Window. The estimation result is demonstrated in Fig. 6. In this figure, we have simulated a scenario in which the number of stations in the network varies over time (i.e., 1, 2, 3, 5, 10, 25, and 15 stations). We refer this scenario to [11]. The result is estimated by counting the number of reserved slots in the Reservation Window. As expected, the result shows that EBA is able to estimate the number of competing stations very accurately.

By means of adjusting the CW value depending upon the number of competing stations, the channel idle time as well as the number of collisions can be further decreased. EBA-2 is developed by implementing this idea.

3.2.4 Early Backoff Announcement -2 (EBA-2)

EBA-2 sets the CW value adaptively. Before randomly selecting a backoff value, EBA-2 counts the number of reservation slots, \( n \), in its Reservation Window, and then sets the CW value to \( 2n \). The rationale behind using this CW value is as follows. Theoretically, EBA-2 does not need to select the next backoff value randomly when there is no change in the group of contending stations over time. However,
In reality, the number of contending stations varies over time. That is, many non-reserving stations such as \( TxQ_{idle,busy} \) stations may exist. Therefore, EBA-2 also needs a collision avoidance scheme to reduce the collision probability as is done in IEEE 802.11 DCF. Setting the CW value to \( 2n \) instead of \( n \) is intended to achieve such a goal. The minimum value of the CW for EBA-2 is represented by \( CW_{\min,EBA-2} \), and we assume that \( CW_{\min,EBA-2} \) is 7. If a station notices that its frame transmission has failed, the CW size follows the binary exponential backoff of the DCF, which resolves collisions in the contention phase. A mechanism of adaptively setting \( CW_{\min} \) value is also standardized as part of the emerging IEEE 802.11e MAC for quality-of-service (QoS) provisioning even though the \( CW_{\min} \) value is determined not by a station as in EBA-2, but by the AP [13][14][15].

In Section IV, we demonstrate that EBA-2 significantly outperforms EBA-1, especially, when there are a small number of contending stations. On the other hand, EBA-1 shows a higher degree of fairness compared to EBA-2. We will compare the performance of EBA-1 and EBA-2 in detail in Section IV. A key advantage of EBA-1 compared to EBA-2 is that EBA-1 stations can co-exist with legacy 802.11 DCF stations more smoothly.

Note that EBA stations and legacy DCF stations may co-exist in the same WLAN. For example, since the EBA is backward-compatible with the legacy DCF, an AP implementing EBA can communicate with both EBA and DCF stations in the same WLAN. In such an environment, the throughput performance will be worse than in the EBA-only WLAN since the DCF stations are not aware of the EBA reservation information. However, the performance should not be worse than in the DCF-only WLAN. On the other hand, when EBA-2 stations and DCF stations co-exist, the EBA-2 stations are likely to underestimate the number of contending stations since the DCF stations do not convey the reservation information.
in its transmitted frames. Accordingly, the EBA-2 stations are likely to maintain a smaller CW compared to the DCF, thus possibly causing more frequent collisions and the starvation of DCF stations.

As will be shown later, EBA-2 could be superior to EBA-1 in many environments. However, EBA-2 performs worse when EBA-2 stations co-exist with legacy DCF stations. On the other hand, the performance degradation when EBA-1 and DCF stations co-exist is not as severe as when EBA-2 and DCF stations co-exist. Accordingly, two EBA algorithms can be used in an adaptive manner. That is, an EBA station, which implements both EBA-1 and EBA-2, can use one of them depending on the existence of legacy DCF stations in the same WLAN.

### 3.2.5 Reservation Window Synchronization

As the Reservation Window is used to maintain not only the station's own backoff information, but also the channel reservation state of the other stations, it is very important to synchronize the offset of Reservation Window (see Fig. 3) with other stations. Basically, the offset is moved to the right for every aSlotTime as the backoff counter decreases during a backoff procedure. As a result, only active stations (\(TxQ_{\text{busy,busy}}\), \(TxQ_{\text{idle,busy}}\), and \(TxQ_{\text{busy,idle}}\) stations) move its offset, while idle stations (\(TxQ_{\text{idle,idle}}\) stations) do not move their offset. Therefore, the synchronization of the Reservation Window among the stations can be broken. To resolve a synchronization problem, EBA attaches not only its future backoff value \(b_{\text{next}}\), but also its current offset value \(i\) in the MAC header as the reservation information. After receiving such reservation information, non-reserving stations, i.e., \(TxQ_{\text{idle,busy}}\) and \(TxQ_{\text{idle, idle}}\) stations, update its offset to \(i\) and set \((i+b_{\text{next}})\)-th slot to \(I_{\text{reserved}}\). In this way, stations synchronize with others repeatedly and recover the offset synchronization when the synchronization was broken.
3.3 EBA Frame Structure

As shown in Fig. 7, the EBA field is added into the end of the existing MAC frame header. EBA stations can smoothly co-exist with DCF stations due to the following characteristic. When the DCF station receives a frame, which is not destined to itself, from an EBA station correctly, it reads the MAC header to set the Network Allocation Vector (NAV) counter based on the Duration/ID field value and regards the EBA field as part of the frame body. This is just fine since the DCF station in consideration is not the destination station of the frame from the EBA station. On the other hand, when the EBA station receives a frame from a DCF station, it reads the MAC header part to set the NAV counter. Note that an EBA station should use the original 802.11 data frame format when it transmits a frame to a DCF station.

An EBA station should determine whether a received frame includes the EBA field or not when DCF stations co-exist in the network. It can be achieved if we force all the EBA stations to maintain the list of neighboring EBA stations. In such a situation, the EBA station can determine the existence of the EBA field by checking the MAC address of the received frame’s transmitter. Actually, this can be implemented very easily in the infrastructure WLANs, since a station always transmits to and receive from its AP in this type of WLANs. An EBA station can determine whether its AP is also EBA-capable during its association phase, and the AP
can also find whether a newly-associating station is EBA-capable during the association phase. Accordingly, in this case, an EBA station shall include the EBA reservation information in all the frames to its AP, and the AP does too in all of its frames to this EBA station.

Another possible way is to define a new data sub-type frame for the EBA transmissions. The frame sub-type is indicated in the frame control field of the MAC header, and a new frame sub-type can be defined without any problem since there are a number of reserved frame sub-types available in the current 802.11 MAC standard.

The EBA field is 20 bits in length and consists of two subfields: the offset field and Reservation Information field (Next Backoff Number). As mentioned in the previous subsection, the offset field is 10 bits long, and is used to synchronize the Reservation Window among stations. The Reservation Information field is also 10 bits long and is used to specify the next backoff value (in number of slots) with the maximum of 1023.

3.4 Supporting Power-Save Mode
The IEEE 802.11 Power-Save Mode (PSM) [1] attempts to reduce energy consumption by putting the station in doze state when possible. In the doze state, the station cannot transmit or receive, thus consuming significantly less power than in active state. Under the PSM, a station wakes up, i.e., goes to the active state, periodically in order to listen to selected beacon frames, which are transmitted by the AP periodically for many different management purposes including power-save mode support.

When the PSM is used along with EBA, the stations that are in the doze state will not be able to gather the reservation information provided by other stations. Therefore, the station that switches from the doze state to the active state desires
to obtain the reservation information prior to contention. Since the AP is always awake, it will maintain a Reservation Window for its network, and include the reservation window information in beacon frames. One bit is enough to represent one slot, where 0 denotes a non-reserved slot and 1 denotes a reserved slot, respectively. The length of the information that is included in a beacon frame can be adaptively determined by the number of reservations occurred during the last beacon period. For example, if there were 20 transmissions and new 20 reservations information are newly marked on the AP’s local Reservation Window, then the AP includes the information in the range of [offset, largest slot number of the newly reserved slot $I_{\text{reserved}}$] from the AP’s Reservation Window into the beacon frame. Since the PSM stations wake up to receive beacon frames periodically, PSM stations can refresh its local reservation window periodically, and hence the negative effects of such PSM stations can be minimized.

4. PERFORMANCE EVALUATION

4.1 Saturation Throughput

In this section, we use the ns-2 simulation [6, 7] to evaluate the performance of EBA in comparison with the legacy 802.11 DCF. We have performed simulations for the following 3 different scenarios in order to simulate the WLAN environments.

- Scenario 1: all nodes can hear to each other without channel errors
- Scenario 2: all nodes can hear to each other with channel errors
- Scenario 3: hidden terminals exist
All simulations are performed in a WLAN environment, with one destination station, i.e., an AP, and 40 source stations, where the source stations are randomly located at the distance of 10~20m from the destination station. Data traffic is generated using constant bit rate (CBR) UDP traffic sources, and simulations are performed in saturated conditions, i.e., there is more traffic than the network can accommodate.

All nodes have no mobility and are awake during throughout the entire simulation time, and hence they can hear all transmissions on the medium. The parameters used in the simulations are shown in Table I, which are based on the IEEE 802.11 network configurations [4].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFS</td>
<td>10 µsec</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 µsec</td>
</tr>
<tr>
<td>aSlotTime</td>
<td>20 µsec</td>
</tr>
<tr>
<td>aPreambleLength</td>
<td>144 µsec</td>
</tr>
<tr>
<td>aPLCPHeaderLength</td>
<td>48 µsec</td>
</tr>
<tr>
<td>Data transmission rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>ACK transmission rate</td>
<td>2 Mbps</td>
</tr>
</tbody>
</table>
4.1.1 Scenario 1: No Channel Errors

First, we simulate in a fully connected topology corresponding to Fig. 8 (a), in which all nodes are within the radio transmission range of each other when there are no channel errors. For the physical radio propagation model, we use the two-ray ground reflection model. The two-ray model predicts the received power as a deterministic function of distance. It represents the communication range as an ideal circle [9].

Fig. 9 presents the throughput performance of 802.11 DCF, EBA-1 and EBA-2 as the number of stations increases from 1 to 40. The throughput of 802.11 DCF suffers as the number of stations increases. The main reason is that the probability of collisions becomes higher as the number of stations increases. When the frame size is large, the throughput decreases faster as the number of stations increases, since the bandwidth loss due to a collision also increases.

The result shows that EBA, i.e., both EBA-1 and EBA-2, outperforms DCF significantly by eliminating collisions almost completely. Accordingly, unlike DCF, the EBA algorithms maintain the maximal throughput as the number of stations increase. EBA-2 outperforms EBA-1 when there are a small number of contenting
stations or a large number of stations, i.e., more than 30 stations. Note that the EBA-2 stations select the initial backoff value from the range of $[0, CW_{\text{min,EBA-2}}]$, whereas the EBA-1 stations select one from the range of $[0, CW_{\text{min}}]$, where the $CW_{\text{min,EBA-2}}$ and $CW_{\text{min}}$ are defined to be 7 and 31, respectively. Therefore, the idling time of the EBA-2 decreases, thus utilizing the channel more efficiently. The throughput of EBA-1 decreases when the number of stations is close to or larger than $CW_{\text{min}}$ because the collision probability among $TxQ_{\text{idle,busy}}$ stations increases.

4.1.2 Scenario 2: Channel Error Effects

In this section, we study the effect of unsuccessful EBA information exchange, by varying the channel error rate. We use the same topology used in previous subsection as shown in Fig. 8 (a) except for the fact that channel errors occur with a certain probability. Channel errors can affect both the frame transmissions and the EBA reservation information sharing. Here, we also use the shadowing model of the ns-2 simulator [9]: the received power at a certain distance is a random variable due to the multipath propagation effects, which are also known as multipath fading.

We consider two error models as follows: (1) error model 1, in which 95% of frames can be correctly received at the distance of 30 m and this percentage decreases with distance increasing, and (2) error model 2, in which 95% of frames can be correctly received at the distance of 20 m and this percentage decreases with distance increasing$^2$. Accordingly, error model 2 represents a worse channel condition. Now, we present and discuss the simulation results for these two cases.

A. Error Model 1: 5% Error at 30m

$^2$ We use the shadowing model, which is part of the standard package of ns-2 simulator, for each scenario by specifying the parameters corresponding to the path loss, shadowing deviation and carrier-sense threshold.
In the network topology described in Fig. 8 (a), the destination station, i.e., the AP, is within the distance of 10–20m from the source stations, while some of the stations are more than 30m away from each other, e.g., station A and B in Fig. 8 (a) and (b). In error model 1 corresponding to Fig. 8 (b), the AP correctly receives most of the data frames transmitted by the stations since all sources are within 20m from the AP, but the stations that are more than 30m apart from the transmitter are not likely to hear the data frames, so that they also cannot receive EBA res-
ervation information correctly. As this is the case, channel errors do not harm the DCF stations, whereas they affect the EBA stations. Fig.10 shows the model where only the EBA is significantly affected by the channel error. Although the EBA stations suffer from the channel error, they still maintain a higher throughput compared to the DCF. This shows that even when the EBA information exchange is not fully functional, the EBA still achieves a better performance compared to the 802.11 DCF.

B. Error Model 2: 5% Error at 20m

In model 2 corresponding to Fig. 8 (c), the error situation is more severe compared to model 1, where the source-destination data frame transmissions are influenced by channel errors in this model. As shown in Fig.11 both DCF and EBA suffer from channel errors, thus resulting in higher collision ratios. Nevertheless, the results show that both EBA-1 and EBA-2 provide approximately up to 10% and 25% improvement over the DCF, respectively.

4.1.3 Scenario 3: Hidden Terminal

In this section, we present the effects of hidden terminals [1]. The hidden terminal problem provokes some problems in EBA. The first problem is caused by the limitation of the transmission range. Since hidden terminals occur, some stations may not hear the reservation information from the hidden terminals. This induces sta-
tions to reserve on the same slot, resulting in collisions at the AP. The other problem is that all the stations may not be synchronized due to the network topologies and different transmission ranges. This means that the stations in the transmission range of a transmitting station sense the channel state as busy, and hence will freeze their backoff value, while the stations out of the range senses the channel state as idle and activates its backoff timer. Accordingly, they will have different Reservation Windows and their offset.

Fig. 12 shows the network topologies used in Scenario 3. The scenario in Fig. 12
consists of two station groups. The stations of each group are hidden to the stations belonging to the other group. That is, stations belonging to sender group 1 in Fig. 12 cannot hear transmissions from the stations belong to sender group 2, and vice versa. We have simulated 4 scenarios in which the numbers of stations in sender groups 1 and 2 in Fig. 12 vary, i.e., (the number of station in group 1, the number of stations in group 2) = (2,3), (5,5), (7,8), (10,10).

As shown in Fig. 13, the throughput for both DCF and EBA diminishes considerably. Nonetheless, the EBA still maintains a higher throughput compared to the DCF. This is in part because stations in each group, which have no hidden terminals, can hear the EBA information from each other in the same group and avoid collisions.

We also have examined the performance of DCF and EBA with RTS/CTS exchange under the same topologies and network configurations used in the previous simulation. The RTS/CTS exchange of EBA is equivalent to that of DCF. This means that the reservation information is only included into data frame header not into RTS or CTS frames, i.e., there is no modification on RTS-CTS frame sizes and inter-frame-spaces (IFSs). Fig. 14 shows the throughput results of DCF and EBA when the RTS/CTS mechanism is used. When we compare these results to Fig. 13, the throughput is improved by eliminating the hidden terminals by RTS/CTS mechanism. In such situations, EBA also has a better performance compared to DCF. The main reason of this improvement is that the collisions between RTS frames were reduced by EBA.

4.2 Short-Term Throughput & Fairness
The simulation of the short-term throughput and fairness is performed for the duration of 100 seconds (in simulation time) in a WLAN environment, with one destination station (which is assumed to be an AP, station ID: 0) and 10 source sta-
As simulated in the previous subsection, data traffic is generated using CBR UDP traffic sources, and simulations are operated in saturated conditions. All nodes have no mobility and are awake throughout the entire simulation time, and hence they can hear all transmissions on the medium. An additional station becomes active every 10 seconds, i.e., the $i$-th source station starts its transmission at time $10 \times (i-1)$ seconds and continues to transmit till 100 seconds. The transmission queue of each source is assumed to be always non-empty. Therefore, there are
contending stations at time interval \([10 \times (i-1), 10i]\). That is, there are 2 stations during 10~20 seconds, 3 stations during 30~40 seconds, and so on.

The reduction of the collision also affects the fairness among the contending stations. Fig. 15 shows the channel occupancy ratio during the period of 90-100 seconds, when 10 stations are contending. In order to be fair ideally, each station should occupy 10% of the bandwidth. However, as shown in Fig. 15, the channel occupancies of the 802.11 DCF stations are uneven. This unfairness is mainly attributed to the difference of each station’s CW value, and the difference of CW value is due to the collision. For example, stations 2, 3, and 8 have little opportunities to transmit compared to the others since they have a large average CW value due to the relatively large number of collisions. Stations 4, 5, and 10 experience the opposite case. Although the fairness of the DCF stations is expected to improve as the simulation time is extended, the EBA algorithms should achieve a better degree of the short-term fairness than that of the DCF thanks to the better collision avoidance. The fairness among the EBA-2 stations is worse than that of the EBA-1, since the EBA-2 stations tend to occupy the channel consecutively.

Fig. 16 compares the throughput variation of station 1 along the time when the DCF and EBA-1 are applied. Station 1 participates in the channel contention from the beginning of the simulation. As a new station starts contending for every 10 seconds, the throughput of station 1 decreases since it has to share the channel with the additional station. The throughput pattern of the DCF has a greater fluctuation compared to that of the EBA-1. This implies that sometimes station 1 transmits very often and at other times only few transmissions are made. This phenomenon can be explained as follows: when the station’s frame collides with others, the backoff duration is exponentially increased, and as a result, only a few transmissions are carried out in a fixed time (100 msec). When the station trans-
mits without a collision while others collide frequently, others become idle for a long time due to the large backoff durations. As a result, the station can have more opportunities to transmit. On the other hand, the station using EBA-1 shows a stable figure. As the collisions almost never occur if the EBA-1 is used, the CW value is almost preserved as \( CW_{\text{min}} \). As a result, most stations have fair transmission opportunities.

### 4.3 Compatibility with DCF

In order to evaluate the compatibility of EBA with DCF, we run simulations with 10 stations. We compare the throughput performance of DCF-EBA co-existence situation with that of pure DCF stations (DCF-only situation). In this simulation, we have simulated with 10 scenarios – only 10 DCF stations (DCF-only), 9 DCFs + 1 EBA, 8 DCFs + 2 EBAs, … , 1 DCF + 9 DCFs and only 10 EBA stations (EBA-only).

We run 6 simulations with different seeds, and each result is marked by a symbol, i.e., “+” for each result and “s” for their average. Figs. 17 and 19 show the throughput ratio to the throughput of DCF-only for the situation of DCF-EBA1 and DCF-EBA2 co-existence, respectively. Figs. 18 and 20 present the results of the fairness index for each co-existence simulation. We use the fairness index defined in [16]:

\[
\text{Fairness Index} = \frac{\left( \sum_i T_i / \phi_i \right)^2}{n \sum_i (T_i / \phi_i)^2}
\]

where \( n \) is the number of stations, \( T_i \) is the throughput of flow \( i \), \( \phi_i \) the weight of the flow \( i \) (we assume all stations have the same weight in simulations, i.e., \( \phi_i = 1 \) for all \( i \)). The fairness index lies between 0 and 1. The closer the value is to 1, the more fair.
From Figs. 17 and 18, we observe that EBA1 stations and legacy DCF stations can co-exist in the same WLAN fairly. The throughput performance will be worse than that of the EBA1-only WLAN since the DCF stations are not aware of the EBA reservation information. However, the performance should not be worse than in the DCF-only WLAN. Moreover, the fairness index is not degraded for the case of DCF-EBA1 co-existence situation. This is because EBA1 uses the same size of CW value as DCF, and also selects next backoff values randomly.
The throughput performance in the DCF-EBA2 co-existence situation is also better than that of DCF-only except the cases of (number of DCF stations, number of EBA2 stations) = (1, 9) and (2, 8). However, the degraded fairness index in Fig. 19 tells us that the number of successful transmissions performed by DCF stations is relatively smaller than that of EBA2 stations. Therefore, DCF stations suffer when EBA-2 stations and DCF stations co-exist.

Due to the reasons mentioned in Section 3.2.4, if EBA stations detected the existence of legacy DCF stations in the same WLAN, they are desired to use EBA-1 algorithm. Otherwise, they use EBA-2 algorithm.

5. CONCLUSION

In this paper, we have proposed a novel distributed reservation-based MAC protocol that can be used for the enhanced IEEE 802.11 WLAN. The proposed EBA is a simple MAC with a minor modification of the 802.11 DCF. Since the proposed EBA is backward compatible with the legacy DCF, both EBA and DCF stations can co-exist smoothly in the same WLAN. We designed the protocol in order to handle various situations encountered in the real network including (1) non-greedy stations, which have frames to transmit from time to time in a bursty manner, (2) the power save mode support, in which stations sleep and wake up periodically, and (3) the support of newly joining stations. Through extensive simulations, we have observed that the EBA achieves a significant increase in the throughput performance as well as a higher degree of fairness compared to the legacy DCF.

We expect that EBA can be improved further. As the future work, we plan to consider the followings. The DCF algorithm selects the backoff duration by choosing a value randomly from the range \([0, CW]\). The EBA algorithm is similar to DCF, except that the station checks if the selected value corresponds to an empty slot in
the Reservation Window. By choosing the backoff value randomly, all DCF stations and newly-arriving EBA stations can avoid collisions when they co-exist.

As EBA comprehends the anticipated channel occupation well by maintaining the reservation information, various backoff value selection algorithms in addition to the random selection can be considered. For example, the round-robin scheduling can be easily implemented by reserving the channel access time in the First-In First-Out (FIFO) order. This means that if EBA selects the backoff value immediately after the last reserved slot instead of a random one, stations will transmit frames back-to-back, thus minimizing the wasted bandwidth due to the backoff procedure.

ACKNOWLEDGEMENT

The authors would like to express sincere thanks to the anonymous reviewers, who provided many invaluable comments to improve an earlier version of the paper significantly.

REFERENCES


