Sequentially Ordered Backoff: Towards Implicit Resource Reservation for Wireless LANs

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***Abstract*—In this paper, we present SOBO, a novel hybrid MAC protocol using sequentially ordered backoff in wireless LANs. SOBO eliminates packet collisions and wasted idle backoff slots by introducing implicit resource reservation into 802.11 DCF. In SOBO, the AP divides time into repeating cycles by beacon frames. Exploiting the implicit information of successful transmission order in every cycle, sequentially ordered backoff in a distributed manner during reservation period is achieved without extra control packets. In addition, we propose a novel scheme to estimate the number of contention stations, and design an adaptive contention window algorithm. We also analyze the robustness of SOBO against message losses in realistic networks with channel errors. The performance of SOBO is verified via extensive simulations with different scenarios. Our simulation results show that SOBO achieves a significant increase in network throughput compared to the legacy 802.11 DCF.**

I. Introduction

The Medium Access Control (MAC) protocol is used to provide arbitrated access to a shared wireless medium. The design of the MAC protocols determines the performance of the network. The contention-based IEEE 802.11 Distributed Coordinate Function (DCF) [1] has become the predominant technology for Wireless Local Area Networks (WLANs). The DCF is a random access scheme, based on carrier sense multiple access with collision avoidance (CSMA/CA) with binary exponential backoff. In DCF, before a station transmits, it executes a random backoff process with a randomly selected backoff counter. When the backkoff counter reaches zero, the station transmits. However, since the random nature of the selection of backoff counter, simultaneous transmissions cause packet collisions. The random backoff period also leads to a certain amount of unused idle backoff slots. Hence, inefficient utilization of medium resource is a main problem in contention-based DCF.

On the other hand, some hybrid MAC schemes make better use of the radio channel to achieve high channel efficiency by introducing resource reservation mechanisms into MAC protocols. In general, the traditional reservation schemes can be classified into polling-based and TDMA-based schemes. The point coordination function (PCF) reserves channel resource via a one-by-one polling scheme. The access point (AP) is served as the centralized point coordinator to provide contention-free services to the stations ordered in its polling list. Only the polled station has the right to transmit. However, the overhead of polling frames degrades the performance of polling-based resource reservation schemes.

The TDMA (time division multiple access) is another popular resource reservation scheme. It avoids packet collisions and reserves transmission times for different stations by an efficient schedule scheme which causes extra signaling overhead. A station transmits only during its scheduled time slots. However, TDMA requires tight time synchronization. Due to the fixed length of time slots, it does not support variable packet size.

In this paper, the proposed SOBO is different from existing hybrid schemes which adopt polling-based or TDMA-based schemes in reservation period. SOBO achieves reservation by carrier sense and backoff procedure, and takes advantage of the complete separation between reservation and contention periods with a dynamic adaptation of the size of contention period within a cycle to support arbitrary number of stations and network dynamics. Unlike TDMA, the packet size is variable in SOBO. In addition, making use of the implicit information of unique and consecutive successful transmission order in every cycle, SOBO makes implicit resource reservation without the exchange of control packets. SOBO improves the network throughput while maintains the scalability of DCF.

In SOBO, a station with non-empty packet queue first transmits with a random backoff counter during contention period. Once its transmission is successful, the station keeps a deterministic, i.e., reserved, backoff counter during reservation period in subsequent cycles until the queue is empty to release the reservation. The deterministic backoff counter value is equal to its successful transmission order value in every cycle. So the values of selected backoff counter for stations in reservation period are ordered and consecutive, and they transmit sequentially in a distributed manner during reservation period in subsequent cycles. In addition, the contention period is adjusted dynamically to avoid congestion which leads to

This work was supported in part by the Natural Science Foundation of China (NSFC) under Grants 61202140 and 61328208, by the Fundamental Research Funds for the Central Universities of China, by the Innovation Foundation of the Chinese Academy of Sciences under Grand CXJJ-14-S132, and by the Program for New Century Excellent Talents in University of China under Grant NCET-13-0548. The work of Y. Fang was partially supported by US National Science Foundation under Grant CNS-1343356.

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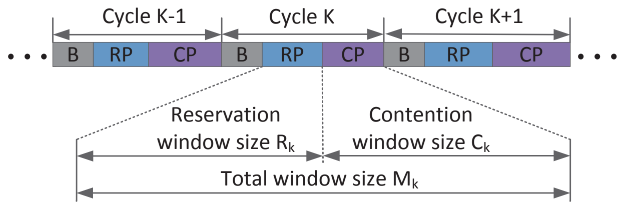

Fig. 1. The repeating cycles

access delay during contention period.

To design SOBO, the biggest challenge is that the reservation is achieved by carrier sense and sequentially ordered backoff. SOBO relies on synchronized decrement of backoff counter. The carrier sense errors, clock offset, and other unexpected factors affect the performance of SOBO. We introduce the beacon frame into SOBO to synchronize stations and initiate the reservation period. In addition, other techniques are proposed to aid SOBO to work well in realistic networks.

The rest of this paper is organized as follows. Section II presents the related work. Section III describes the proposed hybrid MAC scheme. Section IV presents the simulation results, and Section V concludes the paper.

II. RELATED WORK

There have been many studies on hybrid MAC schemes in the literature. The polling-based or TDMA-based reservation mechanisms are used in traditional hybrid MAC schemes [2]–[4]. In addition, there are some novel hybrid MAC schemes that achieve reservation by reserving backoff slots [5]–[9] in WLANs, and the SOBO is inspired by them. In [5]–[7], the basic idea is borrowed from R-ALOHA, i.e., the reservation is achieved by reusing the same slot in every backoff cycle. However, an increase in the number of stations causes a decrease in the probability of finding idle slots in the backoff cycle. Lim et al. [8] finished collision-free transmissions by introducing a joining period with fixed length. Although the fixed joining period can accommodate more station, but the fixed joining period proposed in [8] can not support the simultaneous join of a large number of stations and can not adapt to network dynamics. A more important limitation in [5]–[8] is that these schemes require every station to continuously listen and sense the channel to learn information about the network states. Thus, these schemes lack robustness and may not feasible. Choi et al. proposed the early backoff announcement mechanism (EBA) [9] to reserve channel. The next backoff counter is announced by the MAC header, so other stations do not occupy the same backoff counter. But this scheme requires every station to decode all data packets of other stations.

III. PROTOCOL DESIGN OF SOBO

A. Basic Description of SOBO

In this section, using the sequentially ordered backoff, we present the hybrid MAC scheme, SOBO, which is designed for an infrastructure WLAN. We will start with the introduction of some technical terms.

Beacon Frame: Exploiting the existence of beacon frames in WLANs, the access point (AP) divides wireless medium into repeating cycles by beacon frames. A basic cycle consists of a reservation period (RP) and a contention period (CP). The RP and CP are variable. As shown in Figure 1, in cycle k, the reservation window size is R_k and the contention window size is C_k. The total window size is $M_k = R_k + C_k$. The AP maintains a backoff counter $BC_{AP} = M_k$ at the begin of cycle k. When the backoff counter BC_{AP} reaches zero, the beacon frame of next cycle is broadcast to all stations, and the backoff counter is reset by $BC_{AP} = M_{k+1}$. In cycle $k+1$, the RP is initiated by the beacon frame piggybacking the value of R_{k+1} and M_{k+1}. In addition, all stations are synchronized by the received beacon frame. Note that the existence of RP is due to the successful transmissions of some stations during CP. In other words, a basic cycle only contains the CP initially, and as in 802.11, the the initial contention window size is $C_1 = 15$.

Queue Indicator (QI): To know the state of transmission queue, a 1-bit queue indicator QI is included in the MAC header of data packets. If the station has a non-empty packet queue, it sets $QI = 1$. Otherwise, it sets $QI = 0$. The QI is served as the indicator for stations to reserve or release channel resources.

Contention State: If a station has not reserved a backoff counter, it is in contention state, and transmits in CP. It is a contention station.

Reservation State: If a station has reserved a backoff counter, it is in reservation state, and transmits in RP. It is a reservation station.

Successful Counter (SC): The AP keeps a SC to record the number of successful transmissions with $QI = 1$ in every cycle. The SC is reset to zero at the begin of every cycle. In cycle $k-1$, the AP informs a station that its successful transmission order is SC_{k-1} by the ACK. According to the returned SC_{k-1}, the backoff counter (BC) is set by $BC_k = SC_{k-1} - 1$ in cycle k. For reservation stations, the transmission order in RP in next cycle is equal to the returned successful transmissions order in current cycle.

Unlike TDMA that divides frame into fixed length slots, in SOBO, the contention and reservation periods are backoff counter window, and both are variable. The actual length of a backoff counter is depend on the states (success, collision, or idle). In SOBO, each station employs the standard CSMA/CA scheme and executes the backoff procedure with either a reserved backoff counter during RP or a random backoff counter during CP. When a station succeeds in gaining access with $QI = 1$ during CP, it reserves a deterministic backoff counter for uncontested transmissions during RP in subsequent cycles. Note that if a station unsuccessfully transmits in RP due to unexpect factors, it will revert back to the CP to restart the competition process. So a successful transmission is employed to serve as the implicit information for a station to decide whether it is in CP or in RP. In addition, to fair share of channel, SOBO restricts every station to only transmitting once in every cycle. After its transmission, every station defers

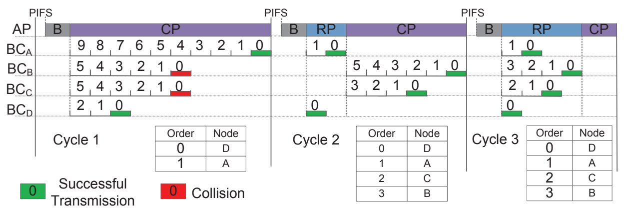

Fig. 2. A basic sequentially ordered backoff with backoff counter (BC)

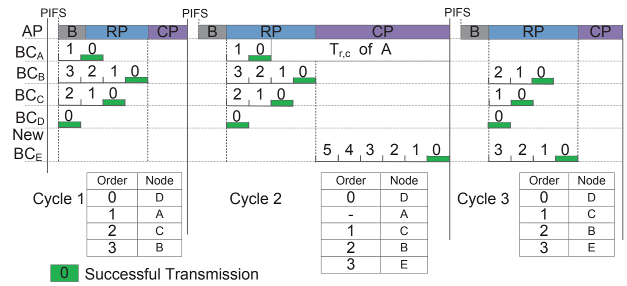

Fig. 3. An illustration for dynamic adjustment of sequentially ordered backoff

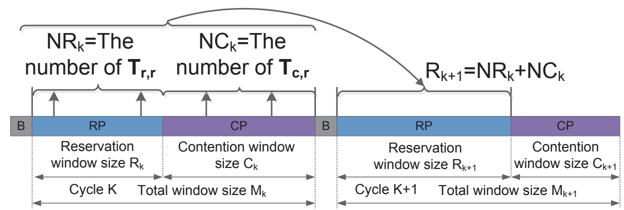

Fig. 4. The variable reservation window size

its next transmission until the arrival of next beacon frame. Once the beacon frame is received at the begin of every cycle, stations reset their backoff counters. Reservation stations get a reserved backoff counter, in the reservation window $[0, R_k - 1]$. Contention stations choose a random backoff counter uniformly from the contention window $[R_k, M_k - 1]$.

B. Sequentially Ordered Backoff

We define some notations for SOBO. The $T_{c,r}$ denotes that a contention station newly gets a reserved backoff counter, and its state will be changed from the contention state to the reservation state. The $T_{r,c}$ denotes that a reservation station releases a reserved backoff counter due to its empty transmission queue, and its state will be changed from the reservation state to the contention state. The $T_{r,r}$ denotes that a reservation station maintains its reservation state due to its non-empty transmission queue.

In SOBO, the backoff counter is decremented by one regardless of the fact that the event is an idle backoff slot, successful frame transmission, or frame collision [10]. Since sequentially ordered backoff, reservation stations can transmit sequentially during RP, i.e., before the data transmission of the station, it only needs to wait for a DIFS after the ACK of the last transmission ends. Figure 2 illustrates the basic operation of sequentially ordered backoff. Initially, contention station A, B, C and D randomly choose backoff counters (9, 5, 5 and 2 respectively) within initial contention window C_1. $T_{c,r}$ station A and D successfully transmit in cycle 1. According to the corresponding successful transmission order, they choose backoff counters 1 and 0 respectively during RP in cycle 2. Since station B and C choose the same backoff counter, they collide with each other in cycle 1. In cycle 2, station B and C randomly choose backoff counters again (5 and 3 respectively) within contention window C_2, and successfully transmit in cycle 2. All stations get reserved backoff counters and transmit sequentially with the implicit order in cycle 3. The backoff counter during RP is equal to the corresponding successful transmission order.

Due to network dynamics in every cycle, reservation stations need to dynamically adjust their backoff counters according to the returned successful transmission order. The dynamic adjustment of sequentially ordered backoff is illustrated by an example in Figure 3. We consider the scenario where a $T_{c,r}$ station E (new entrant) newly gets a reserved backoff counter and a $T_{r,c}$ station A releases the reserved backoff counter. The new $T_{c,r}$ station E needs to wait for the arrival of beacon frames. Based on the received beacon frame containing the contention window size, it randomly selects a backoff counter and successfully transmits in cycle 2. When a reserved backoff counter is released by $T_{r,c}$ station A, the returned backoff counter value for stations that have larger successful transmission order than the station A is decreased by 1. As shown in Figure 3, a new sequentially ordered backoff is formed.

In every cycle, some stations release the reserved backoff counters while some stations newly get the reserved backoff counters. So the reservation window size is variable in every cycle. In cycle k, the number of $T_{r,r}$ is NR_k, and the number of $T_{c,r}$ is NC_k. The NC_k represents the newly added number of stations whose state will be switched from the contention state to the reservation state in cycle $k+1$. As shown in Figure 4, the value of R_{k+1} in cycle $k+1$ is calculated by

$$R_{k+1} = NR_k + NC_k. \quad (1)$$

C. Optimal Contention Window Size

In SOBO, after successful transmission during the CP, stations enter into the RP, which reduces the number of contention stations. However, collisions may occur in CP. To support arbitrary number of contention stations which simultaneously join the network, and guarantee the quick converge to collision-free state, an optimal contention window size is important in SOBO. If contention window size is too small, packet collisions are severe, and if contention window size is too large, the channel bandwidth is wasted due to idle backoff slots. Thus, to fully make the channel resources, it is necessary to dynamically adjust the contention window in every cycle. The adjustment of contention window size is based on the accurate estimation of the number of contention stations during CP in the network. In this part, we first propose a novel scheme to estimate the number of contention stations, then design the adaptive contention window algorithm for CP.

There are three types of backoff counters in CP. *Collision backoff counters*, which means that two or more stations choose it (a collision) and thus no one could transmit correctly. *Success backoff counters*, which means that exactly one station chooses it and the transmission is successful. *Idle backoff counters*, which means that no station choose it.

After a cycle with contention window size C and n contention stations during CP, the AP can observe c_i *idle backoff counters*, c_s *success backoff counters*, and c_c *collision backoff counters*, where $C = c_i + c_s + c_c$. Let n_j denote the number of contention stations involved in jth *collision backoff counter*. Then, we can get the total number of contention stations involved in all collisions, $N_c = \sum_{j=1}^{c_c} n_j$. The total contention stations in this cycle is $N = c_s + N_c$. Let ξ denote the expected number of contention stations selecting a same backoff counter. We can get the estimation of the expected number of contention stations, $\overline{N} = c_s + \xi \cdot c_c$. Since at least two contention stations are involved in a collision [11], a low bound on the estimation of the expected number of contention stations is $\overline{N}_{low} = c_s + 2 \cdot c_c$. In this section, we will give a more precise estimation to improve contention stations estimate performance. Due to the successful transmissions during CP, the number of contention stations is reduced. We are interested in contention stations which incur collisions and will transmit again during CP in next cycle, i.e., the estimation of N_c.

Given n contention stations and contention window size C, the probability that a bacokoff counter is selected by r contention stations is binomially distribution

$$B(r) = \binom{n}{r} (\tau)^r (1-\tau)^{n-r} \tag{2}$$

where τ is the probability that a contention station transmits with a randomly selected backoff counter in CP. Accordingly, the successful probability, idle probability and collision probability are given by

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

$$P_i = B(0) = (1-\tau)^n \tag{4}$$

$$P_c = 1 - P_s - P_i \tag{5}$$

Now we can express the throughput S_{cp} for CP as

$$S_{cp} = \frac{P_s \cdot E[P]}{P_s \cdot T_{succ} + P_c \cdot T_{coll} + P_i \cdot \sigma} \tag{6}$$

where $E[P]$ is the average length of packet payload and σ denotes the duration of an idle time slot. Here, T_{succ} and T_{coll} are the average duration of successful transmissions and packet collisions, respectively.

Let δ be the air propagation delay which is equal to $1us$ and H be the length of MAC header and PHY header. The values of T_{succ} and T_{coll}, depend on the channel access method [12], are calculated by

$$\begin{aligned} T_{succ}^{basic} &= DIFS + H + E[P] + \delta + SIFS + ACK + \delta \\ T_{coll}^{basic} &= H + E[P] + DIFS + \delta \end{aligned} \tag{7}$$

TABLE I
VALUES FOR BOTH BASIC AND RTS/CTS ACCESS METHODS

Access Method	T_{coll} (us)	σ (us)	λ	ξ
Basic	831.4	20	0.219	2.076
RTS/CTS	77.2	20	0.720	2.270

For the RTS/CTS access method, we obtain

$$\begin{aligned} T_{succ}^{rts} &= RTS + SIFS + \delta + CTS + SIFS + \delta + H \\ &\quad + E[P] + \delta + SIFS + ACK + \delta + DIFS \\ T_{coll}^{rts} &= RTS + DIFS + \delta \end{aligned} \tag{8}$$

The maximum aggregate throughput happens when,

$$\frac{\mathrm{d}S_{cp}}{\mathrm{d}\tau} = 0 \tag{9}$$

Solving the above equation, we get the approximate value of τ by

$$\tau^* \approx \frac{1}{n\sqrt{T'_{coll}/2}} \tag{10}$$

where $T'_{coll} = T_{coll}/\sigma$. Given the contention window size C, the probability τ that a contention station randomly selects a backoff counter is $\frac{1}{C}$. Then, we get the corresponding optimal contention window size by

$$C_{opt} = n \cdot \sqrt{T'_{coll}/2} \tag{11}$$

To estimate the number of contention stations, a simple and novel scheme is proposed. We rewrite (2) as

$$B(r) = \binom{n}{r} (\tau^*)^r (1-\tau^*)^{n-r} \tag{12}$$

Then, we discuss the form of the formula (12) as $n \to \infty$ and $r \to \infty$. The approximating expressions of (12) is Poisson distribution

$$P(r;\lambda) = e^{-\lambda}\frac{\lambda^r}{r!} \tag{13}$$

The Poisson distributed with mean $\lambda = nP_e^* = 1/\sqrt{T'_{coll}/2}$.

For an observed backoff counter, the posteriori probability distribution [13] [14] that a backoff counter is selected by r contention stations is

$$P^*(r) = \begin{cases} 0, & \text{if } r = 0, 1 \\ \frac{P(r;\lambda)}{1-P(0;\lambda)-P(1;\lambda)}, & \text{if } r \geq 2 \end{cases} \tag{14}$$

where $P(0;\lambda) = e^{-\lambda}$ and $P(1;\lambda) = \lambda e^{-\lambda}$. Then the expected number of contention stations ξ selecting a same backoff counter is

$$\xi = \lim_{Z\to\infty} \sum_{r=2}^{Z} r \cdot P^*(r) = \frac{\lambda(e^\lambda - 1)}{e^\lambda - 1 - \lambda} \tag{15}$$

According to the calculated value of λ, we can get the corresponding ξ for different access methods. The related values are reported in Table I. To calculate λ for different channel access methods, the corresponding values in (7) and (8) are listed in Table II. The obtained ξ is the upper bound on

Algorithm 1 The Adaptive Contention Window Algorithm

for cycle k **do**
  Record $c_c(k)$
  if $c_c(k) == 0$ **then**
    $C_{k+1} = C_1$
  else
    $C_{k+1} = c_c(k) \cdot \xi \cdot \sqrt{T'_{coll}/2}$
  end if
end for

the estimation of the expected number of contention stations involved in a collision.

The number of *collision backoff counters* during CP is c_c in current cycle. The value of c_c is recored by AP. Then, we can get the estimated number of contention stations $\overline{N}_c$ that incur collisions in current cycle by c_c and (15)

$$\overline{N}_c = \xi \times c_c \tag{16}$$

Finally, according to (11) and (16), the optimal contention window size for next cycle is given by

$$C_{opt} = \overline{N}_c \cdot \sqrt{T'_{coll}/2} \tag{17}$$

Note that if no collision occurs during CP in current cycle, in order to support newly arriving stations in next cycle, the contention window size will be set to the initial value C_1. Based on the calculated contention window size C_k and reservation window size R_k, AP adjusts its backoff counter $BC_{AP} = M_k$ and broadcasts the value of R_k and M_k by the beacon frame at the begin of cycle k. The adaptive contention window algorithm is shown in Algorithm 1.

We emphasize that in TDMA, the dedicated CP introduces fixed overhead when no stations transmit in CP, but in SOBO, the CP is the backoff counter range, which are the idle backoff slots as in 802.11, rather than fixed slots. The idle backoff slots are as short as merely several microseconds.

D. Robustness of SOBO

As discussed above, SOBO works well under ideal network scenario. However, in practice, many factors such as frame loss, channel errors, and other unexpected factors, may affect the performance of SOBO.

Case 1. If some station do not receive the beacon frame, they need to keep silent and wait the arrival of next beacon frame. If a station is broken or leaves the network without noticing the AP, the AP will sense the idle backoff slot in subsequent cycles, and the AP will remove the station from the RP. The returned successful transmission order for all stations whose transmission order is behind this station is decreased by one. The consecutive backoff counter will be recovered in subsequent cycles.

Case 2. If the data packet with $QI = 1$ is received correctly by the AP but the ACK is lost, the station will think this transmission is a failure but AP will think it is a success. As $QI = 1$, AP will reserve a backoff counter for this station in next cycle. But due to the unsuccessful transmission, this station will consider it is in contention state and retransmit during CP in next cycle. So this case leads to a wasted backoff order during RP in next cycle. If no transmission is detected at the expected transmission order in next cycle, the AP will detect this wasted transmission order. This scenario has the same effect as occurring in case 1.

TABLE II
SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
Packet payload	8184 bits	DIFS	50 μs
MAC header	272 bits	SIFS	10 μs
PHY header	128 bits	Idle slot	20 μs
Data frame rate	11 Mbps	ACK	240 bits
RTS	288 bits	CTS	240 bits

IV. PERFORMANCE EVALUATION

A. Simulation Setup

In this section, we present the simulation results by the network simulator OPNET (version 14.5). To evaluate the performance of SOBO, we modify the OPNET model of the IEEE 802.11. The MAC configurations are summarized in Table II, and the initial window size is $M_1 = C_1 = CW_{min} = 15$. These values follow the recommended values in the IEEE 802.11b standard. In our simulations, we consider a typical infrastructure-based wireless LAN environment which consists of an AP and N wireless stations.

B. Saturated Traffic

In this simulation, we show SOBO achieves better saturation throughput than 802.11 DCF with basic access method. Since the traffic is configured to saturate the system, stations always have non-empty queue. As shown in Figure 5, as the number of stations increases, the saturation throughput of DCF decreases sharply due to the increase of collisions. On the other hand, SOBO achieves collision-free transmissions in RP, and the contention window size is adjusted according to network situation. SOBO is not sensitive to the increase of the number of active stations in the network. By the simulation result, we observe that SOBO significantly improves the throughput under the saturated case.

C. Unsaturated Traffic

In this simulation, we consider the performance of SOBO under realistic unsaturated traffic. In this scenario, saturated stations have heavy traffic and others have light traffic. The total number of active stations is $N = 10$. Let θ denote the ratio of the number of saturated stations to the total number of active stations in the network. Figure 6 shows the network throughput versus different θ, which increases from 0 to 1. The saturated stations can fully make use of reserved backoff counter to transmit without restarting the contention state, whereas the unsaturated stations can not fully utilize the reserved backoff counter. The higher ratio of saturated stations, the better performance is achieved. Different traffic situations

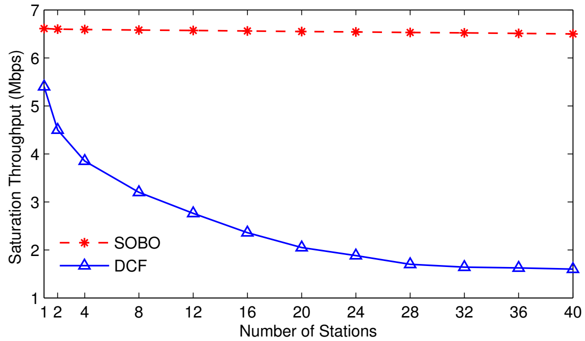

Fig. 5. Throughput versus number of saturated stations

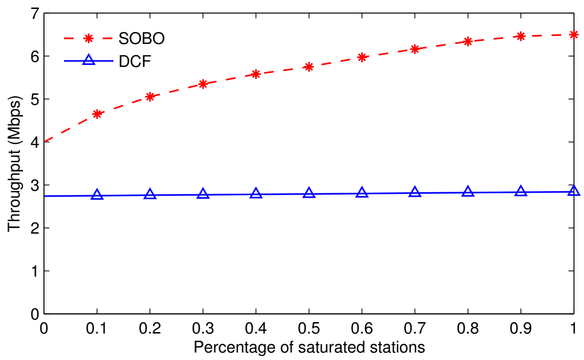

Fig. 6. Throughput versus percentage of saturated stations

make no significant difference to the contention-based DCF, and SOBO still provides higher throughput than DCF.

D. Convergence Time

For given number of saturated stations, there is an optimal contention window size to speed contention stations enter into RP. We define the convergence time as the total time spent for reaching the collision-free state. After all saturated stations successfully transmit in CP, the network converges to collision-free state. In this simulation, Figure 7 shows the average convergence time for a network with different number of saturated stations. Due to the adaptive contention window size adjustment which maximizes the number of successful transmissions during CP in every cycle, the convergence time is small, i.e., the the network access delay of contention stations is small.

V. Conclusion

SOBO is a novel hybrid MAC protocol using a complete separation between reservation and contention period with a dynamic adaptation of contention period in WLANs. There are two key features in SOBO. First, SOBO achieves reservation by carrier sense and sequentially ordered backoff instead of traditional polling or TDMA schemes. Second, SOBO does not require exclusive control packets to achieve the reservation process. The implicit resource reservation is achieved by the successful transmission of the first packet of the transmission queue. Then the station can free to contend for the channel for future transmissions until it releases its reservation. In

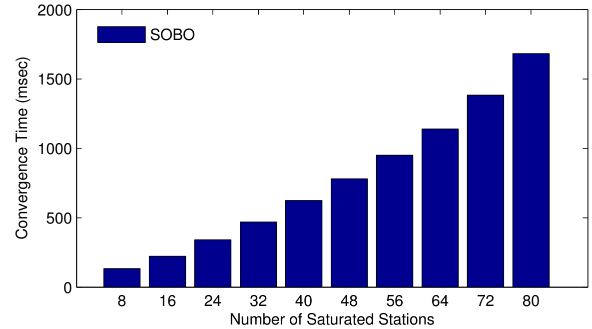

Fig. 7. Convergence time versus number of saturated stations

addition, based on the recorded number of collisions during CP, we propose a simple scheme to estimate the number of contention station, and an adaptive contention window adjustment is designed to support arbitrary number of stations and to minimize the network access delay of contending stations. The contention window size can be shrink or expand depending on the congestion state of the network. The improvement of network throughput is due to the decrease in packet collisions and unused idle backoff slots.

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