

A Hybrid Coordination Function Scheme for WLANs

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Abstract

In this work, we propose a hybrid medium access scheme that can provide a virtually collision-free environment for an infrastructure high-speed WLAN. The proposed hybrid scheme may be viewed as the merger of the standard PCF and DCF schemes. It can efficiently provide the quality-of-service support like the PCF scheme, while utilizing the flexible on-demand CSMA mechanism similar to the DCF scheme. In the proposed scheme, every station employs the standard CSMA mechanism and the master station schedules backoff timers for every client station. The master station sends the backoff timer information together with the data or control frames destined to each given client station. A piggybacking frame exchange mechanism is provided to enhance throughput of the proposed system and a prioritized backoff-timer scheduling scheme is given to provide QoS support. Numerical results show that the proposed scheme outperforms the standard IEEE 802.11 DCF and PCF schemes, and can effectively support prioritized traffic services.

1. Introduction

The original IEEE 802.11 standard specifies two Medium Access Control (MAC) schemes: Point Coordination Function (PCF) and Distributed Coordination Function (DCF). PCF is a central-controlled channel access scheme in which a master station (access point) reserves and manages the channel for every client station in the network. In PCF, a client station can transmit only when polled by the master station. PCF is intended to better support real-time traffic for WLANs in the infrastructure mode. However, PCF is quite inefficient because the channel bandwidth is wasted when client stations with no data to transmit need to respond to a poll command by transmitting a null packet. On the other hand, DCF is a distributed contention-based channel access scheme in which each station employs the carrier sense multiple access technique with collision avoidance (CSMA/CA) and a binary exponential random backoff mechanism for each transmission. DCF is the mandatory access mode specified in IEEE 802.11 and most of wireless LAN (WLAN) deployments commonly rely on this access mode for simplicity, flexibility, and lower cost. Nonetheless, many studies have suggested that the standard DCF scheme is quite inefficient and can be greatly improved by adopting a more efficient random backoff mechanism, e.g., [1]-[4].

In the DCF access mode, several stations may randomly select the particular backoff timer values that cause them to transmit at the same time. In such cases, signal collisions occur and all stations involved must retransmit the given data frame and redo the random backoff procedure with a new backoff timer value. In addition, stations may have to unnecessarily wait longer than required before getting a chance to transmit if they happen to select a large backoff timer value. The collision problem becomes more and more severe as the number of contending stations in the network grows and the size of transmitted data frame increases.

In recent years, many have proposed to solve the collision problem in the standard DCF mode WLAN by dynamically tuning the backoff parameters for each contending station, e.g., [1]-[4]. While these improved backoff schemes greatly reduced the probability of signal collisions in a DCF mode WLAN, they did not fully eliminate the collision problem. In [5]-[7], the early backoff-timer announcement mechanisms have been independently proposed to better solve the collision problem in the DCF access mode. The basic idea is to have each station announce its future backoff timer value prior to the actual transmission so that other stations can avoid using the same backoff timer value at the same moment. The early backoff-timer announcement schemes can effectively solve the collision problem and drastically improve the throughput and delay performance of a WLAN in the DCF mode. However, each client station must hear and keep track of the backoff timer information from all other stations at all time. This requirement may be costly to be implemented for a client device. In addition, client stations may need to initially spend a long time to learn about all of backoff timer values already reserved by other stations in the network. In practice, most WLAN deployments widely rely on the infrastructure topology mode in which there is an access point that may be used to manage and schedule backoff timer values for each client station more effectively.

In this work, we propose a hybrid coordination scheme to enhance performance of an infrastructure WLAN. The proposed scheme utilizes centralized early backoff-timer announcement, acknowledgment piggybacking, and prioritized scheduling mechanisms. The proposed scheme can effectively solve the collision problem of the DCF scheme and provide the desirable quality-of-service (QoS) support. In the proposed scheme, every station employs the standard CSMA mechanism with a slightly modified backoff procedure. A master station is responsible for scheduling backoff timers for all client stations. It shall send the backoff timer information together with the frames destined to each client station. The client station then uses the received backoff timer value to start the backoff procedure associated with the current transmission in the queue. If the client station has not obtained the backoff schedule from the master station due to any reason, it switches to use a random backoff value to start the backoff procedure. A generic algorithm is provided for the master station to allocate backoff slots for each client station using a given QoS scheduling policy. A piggybacking frame exchange mechanism is also provided to enhance capacity of the system. Numerical results show that the proposed scheme outperforms the standard IEEE 802.11 DCF and PCF schemes, and can effectively support prioritized traffic services.

2. Hybrid Coordination Function

The proposed hybrid coordination function scheme may be viewed as a merger between the standard DCF and PCF schemes. It provides a virtually collision-free WLAN environment and can support a desirable quality-of-service requirement as in PCF while maintaining simplicity and on-demand medium access nature as in DCF. The proposed scheme is described in the sequel.

2.1. Backoff Procedure

In the proposed scheme, every station utilizes the standard CSMA mechanism and employs the standard backoff procedure with either a randomly selected backoff timer or a scheduled backoff timer obtained from a master station. The choice of which backoff timer to use for

each station depends on whether it has already obtained a scheduled backoff timer value from the master station prior to the start of the current backoff procedure. If the station has already received the scheduled backoff timer from the master station, it shall use this predefined backoff timer to start. Otherwise, it shall proceed with a randomly selected backoff timer value. After that, the station follows the standard backoff procedure. That is, the station repeatedly decrements its backoff timer by one backoff slot time, "aSlotTime" as defined in IEEE 802.11, if it detects that the medium is idle over each backoff slot. The station may start to transmit the current frame in the queue when its backoff timer reaches zero. The current backoff procedure for this station is temporarily suspended as soon as medium activity is detected, and may be resumed when the medium has been idle again for a specific duration, e.g., PIFS as defined in IEEE 802.11.

Essentially, a client station having a frame to transmit may either use a scheduled backoff timer (if it has already received this information from the master station) or use a random backoff timer (if it has not received a scheduled backoff timer from the master station) to start its backoff procedure. That is, an active station may operate in one of the following modes: the random backoff mode or the scheduled backoff mode. Basically, a client station uses the random backoff mode when it has a frame to transmit under the following circumstances:

- 1) It has just been powered up and has not associated with the master station.
- 2) It has been idle for a long period of time since the previous transmission burst and its assigned backoff timer has expired before the current transmission.
- 3) It is retransmitting a previously unacknowledged frame.

On the other hand, the client station uses the scheduled backoff mode when it has successfully sent at least one frame to the master station and it has correctly received the associated acknowledgment or data frames containing the scheduled backoff timer from the master station. Since normal traffic is quite bursty in nature and each burst typically lasts several frames, client stations are expected to operate in the scheduled backoff mode most of the time, except for the first frame of the burst or the retransmitted frame. In addition, it is less likely that client stations start a traffic burst or retransmit a frame at the same moment. Therefore, the number of stations contending for the medium using the random backoff mode should be much reduced, and so is the chance of signal collisions in the network.

2.2. Random and Scheduled Backoff Slots

A major challenge for the proposed hybrid access scheme is how to design the protocol such that the stations operating in the random backoff mode do not interfere with stations operating in the scheduled backoff mode. One simple approach is to adopt the standard mechanism defined in IEEE 802.11 for coexistence of PCF and DCF, by allowing stations operating in the scheduled backoff mode to transmit during the predefined contention-free period (CFP), while restricting stations operating in the random backoff mode to transmit during the predefined contention period (CP). A drawback of this simple approach is that the channel must be specifically reserved for a specific period of time even though there is no station operating in the random backoff mode. Since stations are expected to operate in the scheduled backoff mode most of the time with the proposed hybrid access scheme, statically reserving channel resource for the contention-based access could lead to an unnecessary waste of channel bandwidth. Furthermore, stations operating in the random backoff mode

may experience long medium access delays because they may have to wait for an extended duration before the contention period begins in each cycle.

Alternatively, we propose to allocate backoff slots in a pre-defined pattern as depicted in Figure 1. The main idea is to separately reserve a certain number of predefined backoff slots for the master station, the scheduled backoff stations, and the random backoff stations. Unlike the former simple physical channel reservation approach, the proposed novel backoff scheduling mechanism does not explicitly reserve the channel airtime for the random-backoff stations, but reserves a number of much-shorter-duration backoff slots instead. Moreover, the stations operating in the random backoff mode do not need to wait for a long period of time until CFP ends in each cycle. Here, the slot reservation is designed such that the random backoff stations can easily determine the locations of allowable backoff slots. Essentially, the random backoff stations can easily determine the location of an allowable backoff slot by first observing a backoff slot used by the master station to transmit information. Then, it is trivial to figure out that an allowable random backoff slot is the next backoff slot following this master station backoff slot, and an allowable scheduled backoff slot is the next backoff slot after this random backoff slot. All client stations shall maintain synchronization to the proposed backoff slot pattern. Each client station may employ a circular-shift clock with a period of 3 tracking this pattern such that the clock value of zero corresponds to an allowable random backoff slot. This clock is incremented every time the station detects that the medium has been idle for a period of PIFS or there is no medium activity over a backoff slot.

Note that the ratio of the random backoff slots and scheduled backoff slots could influence the overall throughput performance of the system. In general, if too many slots are reserved for the random backoff operations, we might end up having too many idle random backoff slots. In contrast, if too few slots are reserved, the access delay for stations operating in the random backoff mode could be undesirably long. In fact, we compute the throughput performance as function of the random and scheduled backoff slot ratios using the IEEE 802.11b parameters. We actually find that reserving fewer backoff slots than suggested in Figure 1 for the random backoff operation is not productive. On the other hand, reserving more backoff slots than suggested in Figure 1 noticeably degrades the throughput performance.

Note also that we have not addressed the issue of hidden terminals in this work. In fact, client stations may not be able to achieve proper synchronization of the backoff slot timing when hidden terminals are present. To address this issue, one may employ the existing techniques to solve the hidden node problem. For example, one may properly adjust the transmitting and carrier-sensing range to reduce hidden terminals as suggested in, e.g. [8]. Alternatively, one may use the out-of-band or in-band busy tone mechanisms, e.g. [9]-[10]. In the future work, we will explore an efficient hidden-node protection mechanism for the proposed scheme.

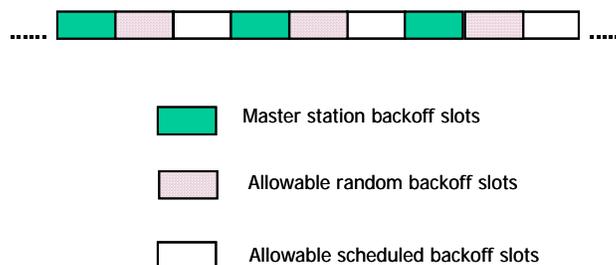


Figure 1. The proposed alternate backoff slot pattern

2.3. Frame Exchange Protocol

In the proposed scheme, the master station may transmit a frame using one of the following standard and newly defined frame types when it gets a chance to transmit during a given master backoff slot:

1) “DATA+ACK+BT”: The master station uses this frame type when it wants to send a data frame to the next scheduled client station in its queue, and at the same time it wants to acknowledge a successful frame reception and convey the new backoff timer value to the previously transmitted scheduled backoff client station.

2) “ACK+BT”: The master station uses this frame type when it wants to acknowledge a successful frame reception and convey the new backoff timer value to the previously transmitted backoff client station, while it has no data destined to the next scheduled client station in its queue.

3) “DATA”: The master uses this standard DATA frame type when it wants to send a data frame to the to the next scheduled client station in its queue, and it does not have to acknowledge a successful frame reception nor convey the new backoff timer value to a previously transmitted scheduled backoff client station.

4) “DATA+ACK+BT+PUSH”: The master station uses this frame type when it wants to acknowledge a successful frame reception and convey the new backoff timer value to the previously transmitted backoff client station, and it wants to send a data frame to a given client station as well as directing this client station to respond using the next allowable scheduled backoff slot.

5) “DATA+ PUSH”: The master station uses this frame type when it wants to send a data frame to a given client station and direct this client station to respond using the next allowable scheduled backoff slot, and it does not have to acknowledge a successful frame reception nor convey the new backoff timer value to a previously transmitted scheduled backoff client station.

6) The master station may not send anything at all if it has no data to send and it does not have to acknowledge a successful frame reception.

Here, the newly defined frame types are formulated based on the standard IEEE 802.11 frame format with the addition of the 2-octet Backoff Timer Value field (if applicable). The previously unassigned value in the Subtype field may be used to identify each of these frame types.

Note that there may be a situation when the master station needs to send a frame to a previously unscheduled client station. In this case, the master station would immediately reserve an available scheduled backoff slot in the queue for this client station. Once it is the time for the master station to send a frame to this client station, the master station would direct this client station to use the next adjacent scheduled backoff slot that has been previously reserved by sending the “DATA+PUSH” frame or the “DATA+ACK+BT+PUSH” frame. In other words, the “DATA+PUSH” frame type and the “DATA+ACK+BT+PUSH” frame type are used to initiate a downlink data burst to a previously unscheduled client station.

On the other hand, a client station operating in the scheduled backoff mode may transmit a frame using one of the following standard frame types when it gets a chance to transmit during its assigned scheduled backoff slot:

- 1) “DATA + ACK”: The client station uses this standard frame type when it wants to send a data frame to the master station as well as acknowledging a successful frame reception.
- 2) “ACK”: The client station uses this frame type to acknowledge a successful frame reception while it has no data to transmit to the master station.
- 3) “DATA”: The client station uses this frame type to send a data frame to the master station and it does not acknowledge a successful frame reception.
- 4) The client station may not send anything at all if it does not have to send a data frame nor an acknowledgment frame to the master station.

Finally, a client station operating in the random backoff mode may transmit a “DATA-RAND” frame to the master station when its backoff timer counter reaches the value of zero and its backoff slot pattern clock indicates that the current backoff slot is the allowable random backoff slot. In this case, upon a successful reception of the data frame from this client station, the master station shall immediately respond with an “ACK+BT” frame after a period of SIFS. Note that here SIFS is the same as defined in IEEE 802.11.

2.4. Backoff Timer Scheduling

In the proposed scheme, the master station can control and manage medium usage by scheduling the backoff timer for every scheduled backoff station including itself. Recall that we arrange the backoff timer schedule such that it has a periodic pattern starting with a master station backoff slot, followed by a random backoff slot, and then a scheduled backoff slot. Here, the master backoff slots are used to convey downlink traffic flows to client stations, while the scheduled backoff slots are used to convey uplink traffic flows from client stations to the master station. Let’s refer to the downlink and uplink backoff slots to and from the i^{th} client station as D_i and U_i , respectively. A generic backoff timer-scheduling algorithm at the master station works as described below:

- 1) The master station maintains a backoff-timer scheduling buffer that is formulated by a circular buffer of length N_{max} (e.g., $N_{\text{max}} = 4096$). Each element of this array is virtually associated with a backoff slot. At initialization, the allowable random backoff slots are initialized to a given value of -1 while the allowable scheduled backoff slots for client stations are initialized to a given value of U_0 and the master station backoff slots are initialized with D_0 . Note that these initial values are arbitrarily selected here at convenience. The buffer initialization shall be performed in accordance to the proposed backoff slot pattern depicted in Figure 1.
- 2) The master station also maintains a master clock. This clock is initialized to zero and is incremented by one (in a circular-shift fashion) every time the standard backoff timer at the master station is decremented by one backoff slot. The period of this master clock may also be conveniently set to N_{max} . Essentially, this master clock keeps track of the backoff slot timing. This clock may be viewed as a pointer referencing to a corresponding element of the scheduling buffer. For example, if the clock value is equal to 5, this master clock pointer references to the 5th element of the scheduling buffer. In addition, every time the master clock pointer moves past a

master backoff slot or an allowable scheduled backoff slot in the scheduling buffer, the element corresponding to this slot is reset to the value of D0 or U0, respectively, indicating that the previous reservation has expired.

- 3) When the master station needs to schedule a backoff timer for a given client station, it examines the allowable scheduled backoff slots for client stations ahead of the master clock pointer to search for available slots. Here, the available slots would correspond to the elements in the scheduling buffer with the value of U0. The master station then arbitrarily selects one of the available slots, based on a given scheduling rule, and shall allocate the selected slot to this client station. In addition, the master station reserves a corresponding master backoff slot that is located just 2 slots earlier for downlink traffic to this client station. Note that when allocating the selected slot, the master station places an ID value of this client station onto the selected element of the scheduling buffer. This implies that the selected slot is reserved for the station with the specified station ID. For example, U5 and D5 denote the uplink scheduled backoff slot and downlink master backoff slot for the 5th client station, respectively.
- 4) The master station shall also determine the corresponding scheduled backoff timer (*BT*) for this client station. For the case of a scheduled backoff client station, *BT* is determined to be the offset between the index of the selected slot and the index of the next backoff slot assigned to the master station. That is,

$$BT = (\text{Index of the selected slot} - \text{Index of the next master station's slot}) \bmod N_{\max}.$$

Note that if the client station transmits during a random backoff slot, the master station must immediately respond with the “ACK+BT” packet. In this case, *BT* is computed as the offset between the index of the selected slot and the current master clock index.

- 5) Finally, the master station shall send out this backoff timer value (*BT*) during the next master backoff slot.

With the proposed backoff-scheduling algorithm, the master station can arbitrarily schedule a backoff timer for each client station based on a given scheduling rule. Figure 2 displays an example of a first-available-slot scheduling scheme with the immediate piggybacking slot allocation. In this example, at the first instant one of the two client stations (S1) operating in the scheduled backoff mode has transmitted a frame and thus requires a new backoff timer value from the master station. The master station assigns the next available scheduled backoff slot in the queue and sends this information to this client station when it transmits during the next master backoff slot. In this case, *BT* = 5 for this instant. At the next instant, a new client station (S3) has just transmitted a frame using the random backoff mode and thus requires a backoff timer value from the master station in order to switch to the scheduled backoff mode. In this case, the master station assigns the first available scheduled backoff slot in the queue, which is located 7 backoff slots away, and promptly sends this information to this client station using the “ACK+BT” frame, after a period of SIFS.

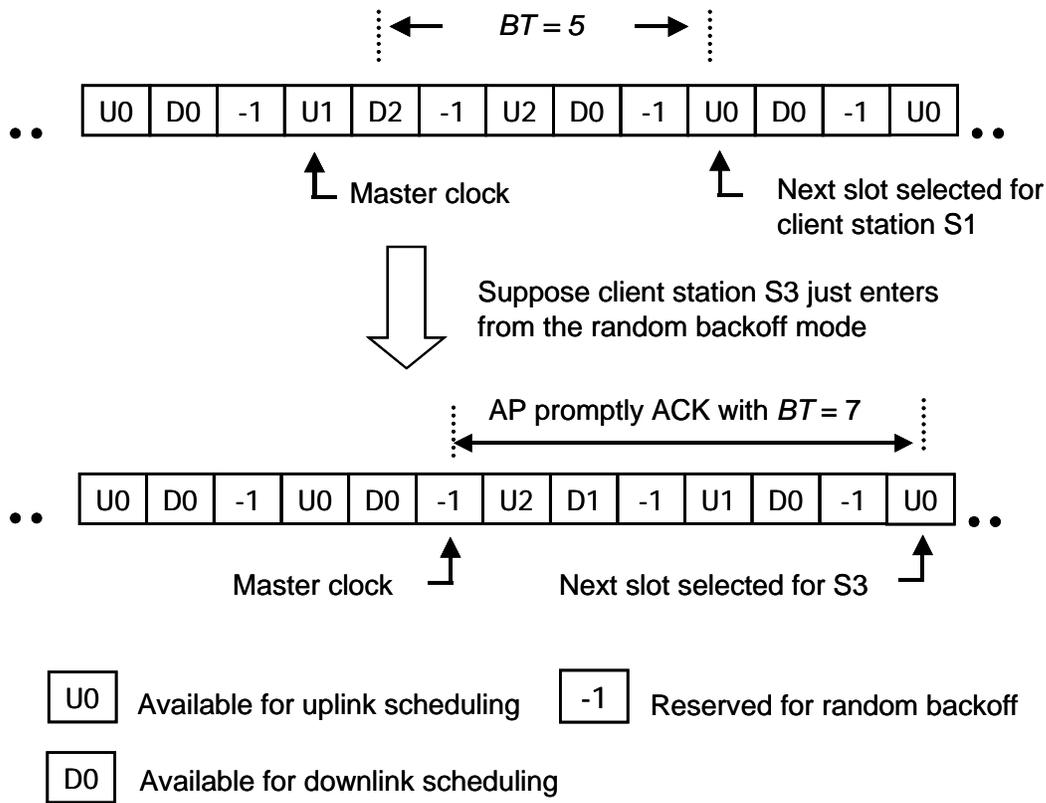


Figure 2. First-available-slot scheduling example

2.5. Quality of Service

The proposed scheme can also support different QoS requirements for different classes of traffic. That is, the master station can enforce different scheduling policies for different client stations. For example, let's consider the case when the master station shall provide QoS support for two different classes of traffic, and let there be N_H high-priority traffic stations and N_L low-priority stations. In addition, the master station shall guarantee that the high-priority stations obtain a larger aggregate share of channel bandwidth than the low-priority stations by a fixed ratio of W . In other words, the aggregate throughput of every high-priority station shall be W times larger than the aggregate throughput of every low-priority station.

In this case, the master station can partition the scheduled backoff slots into two groups: one for the high-priority stations and the others for the low-priority stations. The allocation is done such that there is one low-priority scheduled backoff slot for every W high-priority scheduled backoff slots. The master station shall allocate the

corresponding master backoff slots in the similar fashion. The master station can then enforce the following simple prioritized-first-available-slot scheduling policy. When the master station needs to schedule a backoff slot for a high-priority station, it shall allocate the first available high-priority scheduled backoff slot that is located at least N_H high-priority schedule backoff slots away from the current master clock pointer. Similarly, when the master station needs to schedule a backoff slot for a low-priority station, it shall allocate the first available low-priority scheduled backoff slot that is located at least N_L low-priority schedule backoff slots away from the current master clock pointer.

Figure 3 illustrates a prioritized scheduling example in which there are two high-priority client stations (S1 and S2) and one low-priority client station (S3). In this example, we want the aggregate throughput of the high-priority stations to be 2 times larger than the aggregate throughput of the low-priority station. At the first instant, the low-priority client station S3 has just transmitted and the master station needs to assign the next backoff slot for this client station. The master station looks into its scheduling buffer, locates the first available low-priority scheduled backoff slot, and allocates this slot to this client station. That is, it assigns $BT = 8$ to this client station (S3) in this case. At the next instant, one of the two high-priority stations (S1) has just transmitted and the master station needs to assign the next backoff slot for this client station. The master station looks into its scheduling buffer, locates the first available high-priority scheduled backoff slot, and allocates this slot to this client station. That is, it assigns $BT = 8$ to this client station (S1) in this case.

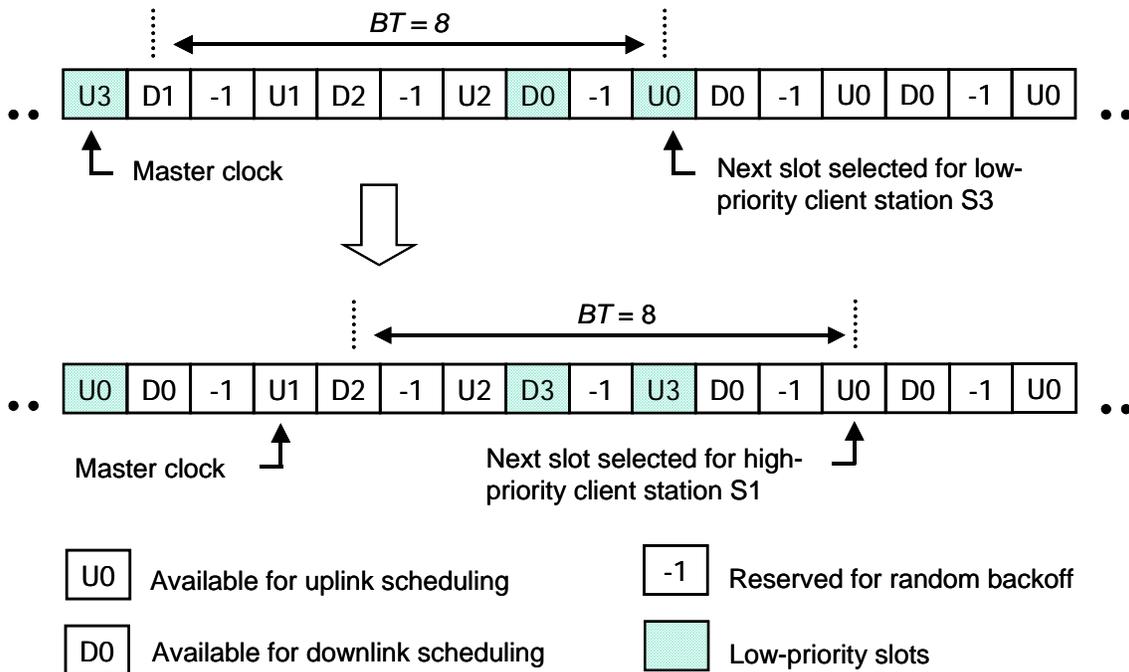


Figure 3. Prioritized scheduling example

3. Performance Evaluation

In this section, we evaluate and compare the throughput performance of the proposed Smart-CSMA scheme and the legacy IEEE 802.11 PCF and DCF schemes in the error-free and hidden-node-free conditions. Here, the performance is evaluated based on the standard IEEE 802.11b parameters. We also assume that all client stations commonly use a fixed-length data payload of 1500 octets.

First, let's consider the throughput performance of the proposed scheme with the first-available-slot backoff timer scheduling scheme and the PCF scheme with a static round robin polling algorithm, given that there are N_s client stations in the networks but only N_a client stations always have data to be transmitted and received while the remaining stations always have empty data traffic. In this case, the aggregate system throughput (S) can be easily determined as the ratio of the total length of useful payload data over the total amount of transmission time. It is not difficult to find that the throughput of the PCF scheme is given by

$$S = \frac{N_a P}{N_a (SIFS + T_H + T_P + \delta) + N_i (SIFS + T_H + \delta)}$$

where P is the length of data payload in a frame, and T_H denotes the PHY and MAC layer header duration, T_P denotes the payload transmission time, δ denotes the propagation delay, and $N_i = N_s - N_a$. On the other hand, the throughput of the proposed hybrid scheme is given by

$$S = \frac{2P}{(2PIFS + 2T_H + 2T_P + T_{slot} + 2\delta)}$$

where T_{slot} denotes the backoff slot duration (aSlotTime).

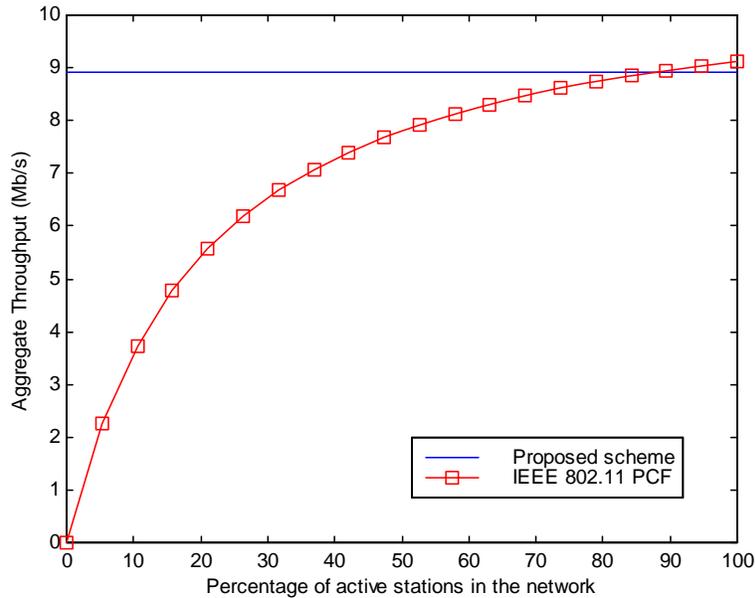


Figure 4. The throughput performance of the proposed scheme vs. IEEE 802.11 PCF

Figure 4 depicts the throughput performance of the proposed hybrid scheme and the standard PCF scheme as function of the percentage active client stations with respect to the total number of client stations in the network (N_a/N_s). It can be seen that the proposed scheme achieves constant and robust performance. It always performs near the best performance level of the PCF scheme. In contrast, the performance of the PCF scheme significantly degrades when the number of inactive stations increases (i.e., the N_a/N_s ratio getting smaller). The large performance degradation is due to the fact that a significant amount of channel bandwidth is wasted when the master station in the PCF scheme needs to send the wasteful Poll frames to the inactive client stations that would in turn respond with the wasteful Null packets. On the other hand, the master station in the proposed scheme would dynamically schedule a backoff slot for a client station only when there is an active traffic flowing to or from that client station.

In addition, we also compare the performance with the standard IEEE 802.11 DCF scheme. In this case, the saturation condition in which every station always has a non-empty transmission queue is assumed. The saturation throughput of the DCF scheme performance can be analytically evaluated using the results provided in [9]. Figure 5 displays the performance comparison of the proposed hybrid scheme vs. the standard DCF scheme. It can be seen that the proposed scheme outperforms the standard IEEE 802.11 DCF scheme. The performance of the proposed scheme is robust while the performance of the DCF scheme significantly degrades when there are a large number of active client stations in the network due to the more severe collision problem.

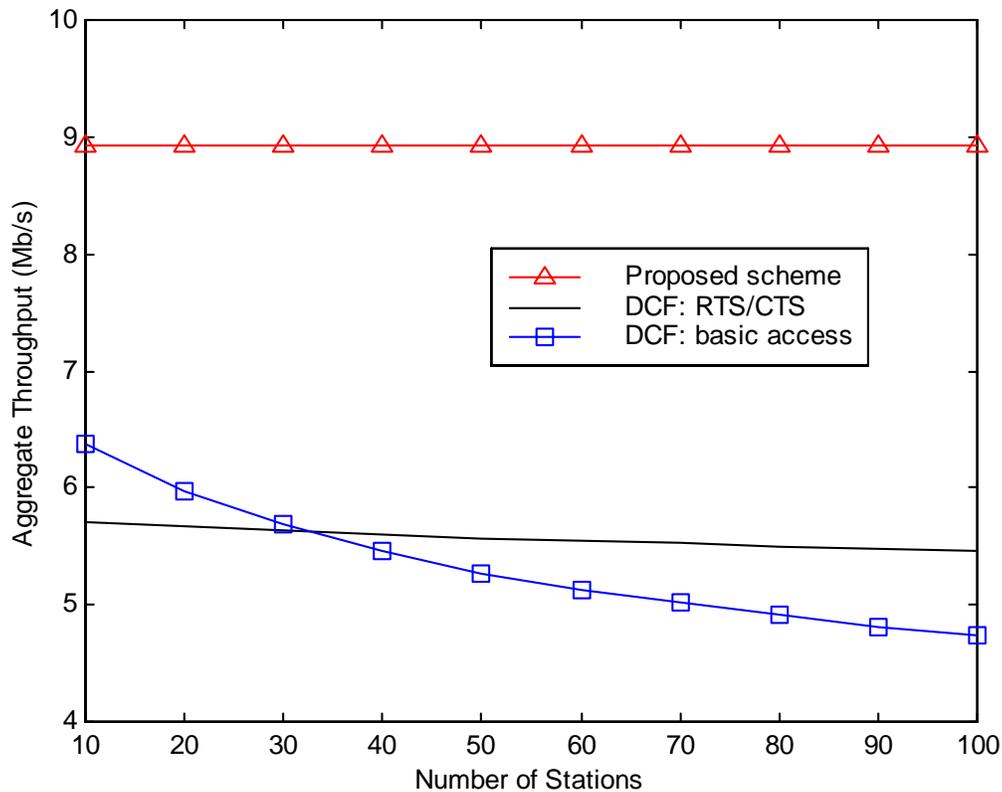


Figure 5. The throughput performance of the proposed scheme vs. IEEE 802.11 DCF

4. Conclusions

In this work, a new hybrid medium access scheme is proposed for high-speed infrastructure WLANs. The proposed scheme combines the advantages of the standard PCF and DCF modes. It can efficiently supports the quality-of-service requirements like PCF while relying on the simple on-demand CSMA channel access mechanism like DCF. In the proposed scheme, a master station schedules the backoff timers for all client stations and send the backoff timer information together with the frames destined to each client station. The client station uses the received backoff timer value to start the backoff procedure associated with the current transmission in the queue. Otherwise, it uses a random backoff value to start the backoff procedure. The master station can use the generic scheduling algorithm provided here to allocate arbitrary slots for a client station. The piggybacking frame exchange mechanism is proposed to enhance the achievable throughput of the proposed system. Numerical results show that the proposed scheme outperforms the standard IEEE 802.11 DCF and PCF schemes.

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