Enhancements of the Modified PCF in IEEE 802.11 WLANs

Apichan Kanjanavapastit and Bjorn Landfeldt

Abstract: **The success of the IEEE 802.11 standard has prompted research into efficiency of the different medium access methods and their support for different traffic types. A modified version of the point coordination function (PCF) called modified PCF has been introduced as a way to improve the efficiency over the standard method. It has been shown through a simulation study and a mathematical analysis that channel utilization can be much improved compared to the standard, in case there is no so-called hidden station problem. However, under the hidden station problem, the efficiency of the modified PCF would obviously decrease.**

In this paper, some enhancements of the modified PCF are introduced. Firstly, we propose a retransmission process to allow frames involved in collisions to be retransmitted. Then, we propose a collision resolution mechanism to reduce the frame collision probability due to the hidden station problem. In addition, we propose a priority scheme to support prioritization for different traffic types such as interactive voice and video, and real-time data traffic in the modified PCF. To prevent the starvation of one low priority traffic, minimum transmission period is also guaranteed to each traffic type via an admission control algorithm.

We study the performance of the modified PCF under the hidden station problem and the performance of the modified PCF with priority scheme through simulations. To illustrate the efficiency of the priority scheme, we therefore compare its simulation results with those of some standardized protocols: The distributed coordination function (DCF), the enhanced distributed channel access (EDCA), the PCF, and our previously proposed protocol: The modified PCF without priority scheme.

The simulation results show that the increment of delay in the network due to the hidden station problem can be reduced using the proposed collision resolution mechanism. In addition, in a given scenario the modified PCF with priority scheme can provide better quality of service (QoS) support to different traffic types and also support a higher number of data stations than the previous proposals.

Index Terms: **Collision resolution, distributed coordination function (DCF), enhanced distributed channel access (EDCA), hidden station, IEEE 802.11, medium access control, multimedia, point coordination function (PCF), quality of service (QoS), wireless LAN (WLAN).**

I. INTRODUCTION

The IEEE 802.11 wireless local area network (WLAN) standard [1] has been the most popular among current WLAN technologies. Currently, 802.11 interfaces are pre-installed in many laptops and PDAs. In addition, wireless networks are being deployed in many organizations, homes, and public areas and even commercial rollouts are taking place.

As the increment of the widespread use of the WLANs, the demand of new applications including multimedia applications such as voice, video, and interactive games has been growing rapidly at the same time. One of the keys to these multimedia applications behaving well lies in the medium access control (MAC) sublayer defined in the IEEE 802.11 standard.

The fundamental access mechanism in the IEEE 802.11 MAC sublayer is the distributed coordination function (DCF). The DCF is a contention-based protocol, which uses the carrier sense multiple access with collision avoidance (CSMA/CA). Since in the DCF mode, wireless stations have to contend to access the wireless medium, the medium access delay for each station cannot be bounded during high load conditions. Thus, the DCF can support only the asynchronous data transmission on a best-effort basis. In order to support any real-time traffic such as voice and video, the point coordination function (PCF) has been another MAC protocol in the IEEE 802.11. The PCF is based on a centralized polling protocol where a point coordinator (PC) located in an access point (AP) provides contention-free services to the wireless stations ordered in a polling list.

Since the bandwidth of the wireless channel is limited, spectrum utilization becomes of primary concern. However, it was noted before the release of the standard that the PCF performs badly due to polling overheads and the use of null frame resulting in a low number of possible voice conversations [2]. To overcome this problem, we have proposed a modification of the PCF called modified PCF which has a capability to increase the channel utilization by avoiding the use of polling, null, and acknowledgement frames. We have shown that the utilization of wireless channel can be significantly improved using the modified PCF in case there is no so-called hidden station problem, through both a simulation study [3] and a mathematical analysis [4]. However, if there are hidden stations in the system using the modified PCF, there might have frame collisions and then the channel utilization would decrease as shown in [4].

In order to deal with the hidden station problem which results in frame collisions, in this paper, we then propose a retransmission process and a collision resolution mechanism. Using the retransmission process, frames involved in collisions can be retransmitted. For the collision resolution technique, stations presumed as hidden stations are separately polled using the standard PCF. This method can therefore avoid the collisions due to the hidden station problem.

As the demand for quality of service (QoS) support in wireless networks grows, the IEEE 802.11e task group is defining a

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new MAC protocol called enhanced distributed channel access (EDCA) [5]. Although the fundamental access mechanism of the EDCA is still based on the CSMA/CA, it can provide channel access differentiation to different types of traffic. From this differentiation, it is possible to give different priorities to different classes of traffic. This means the higher priority, the faster to access the wireless channel. Thus, a good QoS can be given to the stations that carry high priority traffic streams.

In order to differentiate between different types of traffic and improve the support to QoS sensitive applications in the modified PCF, we also propose to use a priority scheme together with the protocol in this paper. The proposed priority scheme can support not only the voice and video traffic streams but it can also support data applications, e.g., telnet, command/control, and interactive games which are sensitive to the delay (around 1 sec [6]). Since various traffic types can be supported in the proposed priority scheme, we therefore use an admission control algorithm to guarantee a minimum transmission period of each traffic type.

We investigate the performance of the modified PCF under the hidden station problem when using the retransmission process and the collision resolution mechanism through a simulation study. The simulation results show that the hidden station problem leads to an increment in the average delay of the simulating network. However, the delay can be reduced if the collision resolution technique is applied with the modified PCF.

For the investigation of the priority scheme, we simulate and compare the results of the proposed priority scheme, the DCF, the EDCA, the PCF, and the modified PCF without priority scheme. The results show that the modified PCF with/without priority scheme can support a higher number of data stations than the other protocols. In addition, the modified PCF with priority scheme provides better QoS support than the modified PCF without priority scheme in a given scenario.

II. RELATED WORK

Two ways of implementing priority schemes in the standard PCF were proposed in [7]. In the first scheme, wireless stations can transmit traffic in order of priority so that higher priority traffic (i.e., voice and video traffic) is transmitted before lower priority traffic (i.e., data traffic). In the second scheme, the PC divides a polling list into high priority list for QoS sensitive transmissions and low priority list for best effort data transmissions. Even though simulations showed that the performance of the normal PCF can be improved by the two priority schemes, the overhead problem of the PCF still exists.

A modified version of the PCF called M-PCF for implementing enhanced QoS support was proposed in [8]. In the M-PCF, the PC starts by polling the first station in its polling list. Then, the second station in the list is allowed to automatically access the channel without the PC issuing another polling frame. In addition, if a station receives a real-time frame from the PC, it does not have to return an acknowledgement. However, in the M-PCF, the PC still sends a polling frame even if a station does not have any data to transmit. Moreover, the M-PCF does not provide a collision resolution technique to resolve the collision problem, which occurs due to the hidden station problem. Therefore, the scheme still suffers from relatively poor bandwidth utilization.

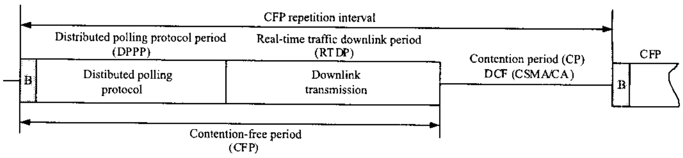

Fig. 1. Channel transmission periods in the modified PCF.

A protocol called Superpoll [9] was introduced to increase the reliability of receiving polling frames in the PCF. The protocol includes a list of stations that will be polled during a current contention-free period (CFP). In addition, a chaining mechanism was proposed to improve the reliability of the protocol by attaching a Superpoll message containing a list of the remaining stations to be polled in every sent frame. In the Superpoll protocol, if a station has no data to send it instead sends a null frame, which still wastes bandwidth. Moreover, the Superpoll message, which is appended to the header of every sent frame, decreases the channel utilization. Last of all, this scheme can effectively operate only with traffic where the frame size is constant (e.g., voice traffic) because each station in the list has to set a pre-calculated timeout.

A reservation CSMA/CA was proposed in [10]. The transmission time of this protocol during the CFP is slotted; therefore, a number of time division multiple access (TDMA) slots is created. Since the reservation CSMA/CA is based on the TDMA, it has the problem of the flexibility to support different real-time traffics which are generated by various encoders since the transmission cycle of the protocol is fixed.

A contention-based multipolling mechanism called contention period multipoll (CP-multipoll) was proposed in [11]. The concept of the CP-multipoll is to use the DCF to access the wireless channel. Different stations are given different backoff time values and therefore, the polling order as used in the PCF is transformed into contending order. Since the protocol uses the request-to-send (RTS) and clear-to-send (CTS) messages to avoid collision between contending stations due to the hidden station problem, the wastage of bandwidth still remains.

The hybrid coordination function controlled channel access (HCCA) has been proposed to replace the PCF in the upcoming IEEE 802.11e standard [5]. Since the HCCA is going to replace the PCF, it is of benefit to compare its operation with the modified PCF. As stated in the draft of the IEEE 802.11e, the basic access of the HCCA is still based on the centralized polling protocol as used in the PCF. However, they are different in that, in the HCCA, the PC can poll wireless stations associated in a polling list during the contention period (CP). Therefore, the overall throughput and medium access delay using the HCCA can be effectively improved. Although the two metrics can be improved, the problem as occurs in the PCF still remains. This is due to the operation of the HCCA still being based on the centralized polling protocol as used in the PCF. As mentioned in the introduction section that the modified PCF avoids the use of polling and null frames, the performance of our proposal should therefore not be limited to only the improvement of channel utilization but the throughput and medium access delay would be

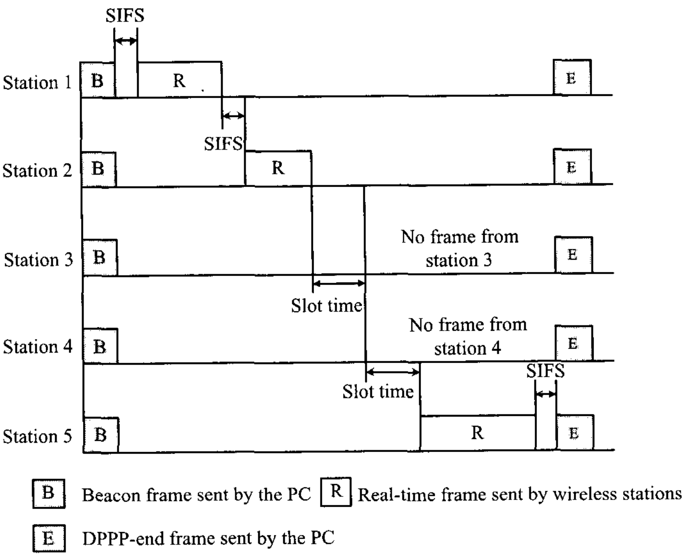

Fig. 2. Access procedure of the DPP.

improved if our protocol could work during the CP as in the HCCA.

III. THE MODIFIED POINT COORDINATION FUNCTION (MODIFIED PCF)

A. *Introduction*

The modified PCF was first introduced in [4]. Its main feature is that it can improve the utilization of the wireless medium by reducing the overheads (i.e., polling overheads, null frames, and MAC-level acknowledgment) as used in the standard PCF. As seen in the Fig. 1, during the CFP the channel transmission time is divided into two transmission periods: The distributed polling protocol period (DPPP) and the real-time traffic downlink period (RTDP). Any wireless station already associated in a polling list sends its real-time traffic to the PC during the DPPP. On the other hand, the PC sends real-time traffics destined to wireless stations during the RTDP. A distributed polling protocol (DPP) is the mechanism used to control the accesses of stations to the medium during the DPPP.

B. *Distributed Polling Protocol (DPP)*

To transmit any real-time information in the DPPP, a wireless station has to be in a polling list. After the station has been added to the polling list, the PC returns a 16-bit polling identification (polling ID) number assigned to that station. To initiate a DPPP as displayed in Fig. 2, after the point coordination function inter-frame space (PIFS) has elapsed, the PC broadcasts a beacon frame (i.e., B frame in Fig. 2) to every wireless station in a basic service set (BSS). Since additional fields such as number of polling IDs and polling IDs will be added in the beacon frame as shown in Fig. 3, the transmission order of a station can be identified among the wireless stations. The stations that cannot receive the sent beacon frame are not allowed to transmit in a current period. On the other hand, if the sent beacon frame can be received, the station, which gets the first transmission order, is allowed to transmit a frame (i.e., R frame in Fig. 2) after the short inter-frame space (SIFS) has elapsed. The following stations in the polling sequence should sense into the medium to check whether the medium is in idle or busy state. Note that the sensing time of the idle period is dependent on the underlying physical layer. In case of the direct sequence spread spectrum (DSSS) physical layer which is considered in this paper, the stations shall determine an idle period by waiting to hear a transmission during a slot time. If a station does not have a frame to transmit, it just leaves the channel so that the next station in the polling sequence will sense this event and start to send its frame in a slot time. After all stations have been polled, the PC will finish the current DPPP by transmitting a DPPP-end frame (i.e., E frame in Fig. 2).

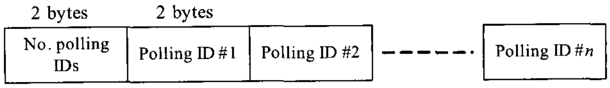

Fig. 3. Additional fields added in beacon frame.

It is possible that a number of stations in the sequence cannot be able to transmit its frame during a DPPP since the end of the DPPP is reached before its turn to transmit. Therefore, to achieve the fairness among stations in the polling list, each station would be circularly shifted its transmission order by one position in the next DPPP. The new polling sequence is then announced in the beacon frame of the next DPPP.

C. *Retransmission Process of Collided Frames*

Since the so-called hidden station problem will normally occur in wireless networks, it is necessary for the modified PCF to have a retransmission process for collided frames. In order to describe the retransmission process, assume that station 3 cannot sense the transmission commenced by station 2 as shown in Fig. 4. Hence station 3 will start its transmission after a slot time and therefore a collision will occur. The PC and other stations that can hear the transmissions of both two stations will detect the collision by using the verification of the cyclic redundancy code (CRC) in the PHY level (i.e., a collision will lead to the fail of the CRC verification). Since there might be some stations that cannot detect the collision, the PC shall transmit a jamming signal which is just an alternating zero-one pattern. Note that the duration of a jamming transmission is equal to the transmission time of the preamble of the PHY plus the transmission time of the maximum frame size admitted in the network. Since the stations that cannot detect the collision by themselves and the stations involved in the collision shall receive the jamming signal for the set duration, they then know that a collision has occurred in the channel. All stations will then wait for the retransmission process initiated by the PC to take place.

Since the PC has identified that station 2 started its transmission but the transmission was not successful, the cause of the unsuccessful transmission should come from the transmission of a following station in the polling sequence. Although the PC cannot identify exactly which station is the cause of the collision, the PC knows that station 3 is the next station in the polling sequence that will get the right to transmit. Therefore, the retransmission process should involve stations 2 and 3 only. To start the retransmission process, the PC sends a polling frame

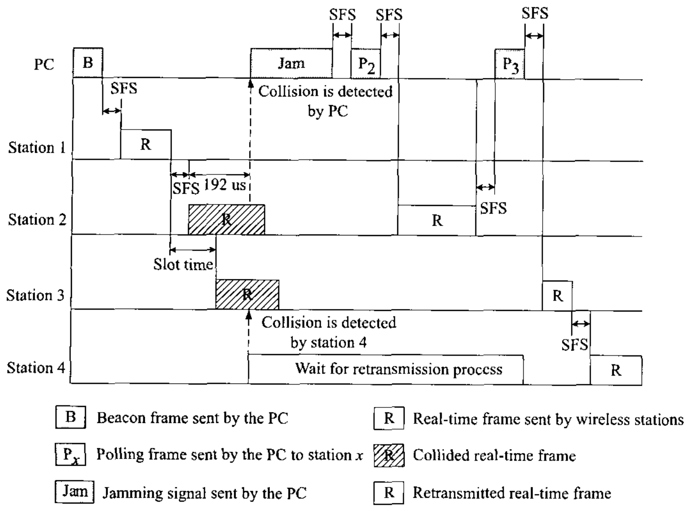

Fig. 4. Operation of the retransmission process.

1st Round	1	2	3	4	5	6	7	8	9	$C_4 = 1, C_7 = 0$
2nd Round	9	1	2	3	4	5	6	7	8	$C_4 = 2, C_7 = 0$
3rd Round	8	9	1	2	3	4	5	6	7	$C_4 = 3, C_7 = 0$
4th Round	7	8	9	1	2	3	4	5	6	$C_4 = 3, C_7 = 1$
5th Round	6	7	8	9	1	2	3	4	5	$C_4 = 3, C_7 = 2$
6th Round	5	6	7	8	9	1	2	3	4	$C_4 = 3, C_7 = 3$
7th Round	4	5	6	7	8	9	1	2	3	$C_4 = 4, C_7 = 3$
8th Round	3	4	5	6	7	8	9	1	2	$C_4 = 5, C_7 = 3$
9th Round	2	3	4	5	6	7	8	9	1	$C_4 = 6, C_7 = 3$

Cx: Collision count of station x

Fig. 5. Operational example of presuming a hidden station.

to station 2. The polled station responds to the poll by retransmitting its frame to the PC. After the PC receives the frame, it sends another poll to station 3. After receiving the last poll, the remaining stations in the polling sequence can resume to the normal operation.

D. Collision Resolution Mechanism

Since collisions result in retransmission overheads, it is therefore beneficial for the modified PCF to implement a collision resolution mechanism to minimize the number of collisions. Apart from overheads, affected stations will also experience increased medium access delay due to the retransmission process. We investigate the effects of this problem in our simulation results afterward in Section V-B.

The concept of the proposed collision resolution is based on the observation that a hidden station should encounter with the highest number of collisions. Since the PC can identify the station which currently has the right of transmission, it can then count the number of collisions of each station. Thus, the PC presumes a hidden station by counting the number of collisions and comparing it to a collision threshold which can be set according to the number of stations associated with the PC. For example, the collision threshold can be set at the ceiling of half of the number of the associated stations in order to reduce the delay of presuming a hidden station.

The following example illustrates the operation of presuming a hidden station. In the example, we assume that a wireless network consists of 9 wireless stations and the collision threshold is set to 5. In addition, each station generates data only one frame per DPPP round. Furthermore, stations 4 and 7 cannot sense transmissions of each other. As illustrated in Fig. 5, at the first round, the frame transmitted by station 4 collides with that of station 7; thus, the collision count of stations 4 and 7 is 1 and 0, respectively. The operation proceeds to the fourth round where the transmission order of station 7 is before the transmission order of station 4 due to the circularly shifting process as described in Section III-B. At this fourth round, the collision count of stations 4 and 7 is 3 and 1, respectively. The same operation is progressive until it reaches to the ninth round where the collision count of stations 4 and 7 is 6 and 3, respectively. Since the collision count of station 4 is now higher than the set collision threshold, the PC can assume that station 4 is a hidden station.

After the PC identifies a station presumed to be a hidden station, it relocates the station to a special list for hidden stations. Stations in the special list will be polled separately using the access mechanism of the PCF at the end of a DPPP. However, this method is only efficient for hidden stations that are stationary. To deal with mobile stations, the dwelling time to stay in the special list of each station can be set. In addition, this will also rectify wrongly identified hidden stations.

IV. THE MODIFIED PCF WITH PRIORITY SCHEME

A. Introduction

The modified PCF can be enhanced to provide priority for different types of real-time traffic. To implement the priority scheme, we first apply the priority to access category (AC) mappings as used in the IEEE 802.11e. The traffics generated by various applications can then be classified into one of the four ACs as shown in Table 1. Any data applications such as command/control and interactive games that require short one-way delay as recommended in [6] can also be supported in the proposed priority scheme. Since these applications not only require short delay but also loss-less transfer, special support is needed in the proposed priority scheme. Thus, positive acknowledgment (ACK) is used for this type of traffic even though the use of ACKs might decrease the channel utilization. However, this does not apply to transmission of other real-time traffic such as voice and video.

B. Channel Transmission Times in the Priority Scheme

In the proposed priority scheme the transmission period in the DPPP is divided into four periods corresponding to the number of ACs. The reason for separating the transmission periods is to reduce the effect of lower priority traffic delaying higher priority traffic. The separation will also reduce the probability of the hidden station problem if a station with traffic belonging to one

Table 1. Priority to access category mappings.

Priority	Access category (AC)	Traffic type
1	0	Best effort
2	0	Best effort
0	0	Best effort
3	1	Video probe
4	2	Video
5	2	Video
6	3	Voice
7	3	Voice

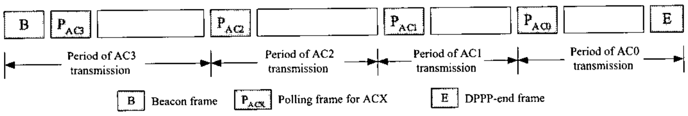

Fig. 6. Transmission periods for different ACs in the DPPP.

AC is hidden from a station with traffic belonging to another AC. As seen in Fig. 6, AC3, which is the highest priority, is transmitted first and then AC2, AC1, and AC0 follows. Note that a polling frame is sent by the PC to notify the beginning of each AC.

To prevent the starvation of one low priority AC, the proposed priority scheme then guarantees a minimum transmission period for each AC. The value of the minimum transmission length can be set corresponding to the AC priority where higher priority translates to a longer guaranteed period. For example, the guaranteed transmission period of AC3, AC2, AC1, and AC0 can be respectively 40 percent, 30 percent, 20 percent, and 10 percent of the maximum transmission period allowed in the CFP (CFPMaxDuration). Note that the concept to guarantee the minimum bandwidth in the PCF can also found in [12]. Although one AC, e.g., AC2, gets lower minimum transmission length than one higher priority AC, e.g., AC3, the lower priority AC could still get some additional transmission length if the allocated transmission length of the higher priority AC after used is available. Note that the CFPMaxDuration can be found in Section 9.3.3.3 of [1].

C. Operation of the Priority Scheme in Uplink Transmission

The operation of the proposed priority scheme during the DPPP can be described as follows. Any traffic streams in each AC are transmitted in a dedicated transmission period during the DPPP. The PC will transmit a polling frame at the beginning of the transmission period of each AC to indicate the length of transmission period and transmission orders of stations; thus, the fields indicating the number of polling IDs and polling IDs have to be added into a normal polling frame as in the beacon frame (see Fig. 3). The PC still uses a beacon frame at the beginning of a CFP to indicate the transmission period of the whole CFP to all wireless stations. After receiving the polling frame issued for an AC, stations that have their traffic streams belonging to that AC transmit their traffic according to the DPP as usual. Traffic in an AC cannot be transmitted after the maximum transmission time indicated in the polling frame has been reached.

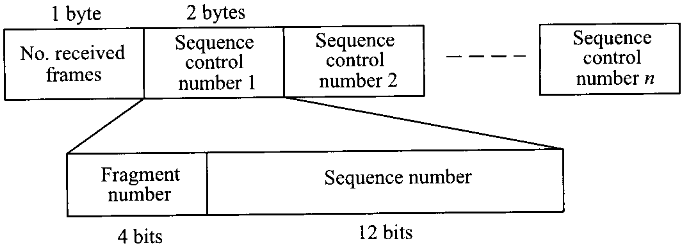

Fig. 7. Additional headers to implement contention-free group acknowledgment frame.

D. Operation of the Priority Scheme in Downlink Transmission

Normally, the downlink transmission is much easier to control than the uplink transmission since the PC is the only station allowed to transmit. In the original modified PCF, during the RTDP, the frame scheduling in the downlink transmission is based on a first-come-first-serve (FCFS) basis. However, in the proposed modified PCF with priority scheme we use a priority queuing scheme. In this priority queuing scheme, a frame received at the PC is inserted in the downlink buffer according to its priority. Thus, higher priority frames can be inserted closer to the head of the transmission buffer than the lower priority frames. This results in lower medium access delay for higher priority traffic.

E. Positive Acknowledgement for Data Transmission

The proposed priority scheme can be used to support transmission of data, which requires both short delay and loss-less transmission. To achieve this, positive ACKs are used to notify a sender, whether its recipient received a frame correctly. In this scheme, a recipient shall transmit an ACK frame whenever a frame is received correctly. However, since a wireless station can transmit a number of frames in one DPPP, the PC shall acknowledge all the frames received from a single station simultaneously to reduce the overhead. This method referred to as a group acknowledgement which also will be added in the upcoming IEEE 802.11e. The idea of the group acknowledgement can be also used in our work by allowing a wireless station to acknowledge multiple frames sent by the PC during one RTDP. Note that the piggybacking technique as used in the standard PCF can still be applied with this group ACK.

We define a new contention-free group acknowledgement (CF-GACK) frame to be used just for our work. Even if a station only receives a single frame, the CF-GACK can be used by indicating the number of received frames to be one. The structure of the defined CF-GACK is as follows. A sender can identify whether an individual transmitted frame has been lost or corrupted by using a sequence control number consisting of a 4-bit fragment number and a 12-bit sequence number. The number of received frames and their sequence control numbers are included in the structure of the CF-GACK. As shown in Fig. 7, a CF-GACK contains a 1-byte field indicating the number of received frames coupled with fields indicating the number of sequence control numbers (corresponding to the number of received frames). These additional fields can be added in the header of the standard data frame structure defined in the standard 802.11.

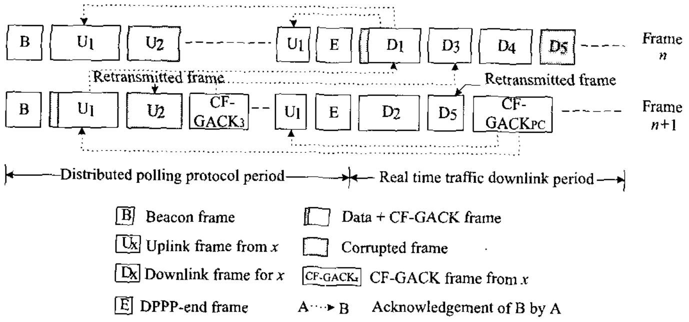

Fig. 8. Operation of the positive acknowledgement.

By using the positive ACK, if a sender cannot receive a CF-GACK frame sent by its corresponding recipient, this implies that the transmitted data frame was corrupted or lost. Then, the sender can retransmit the lost frame in the next DPPP in case it is a wireless station or the RTDP in case it is the PC.

Fig. 8 shows an example of the operation of the positive ACKs in the modified PCF without priority support. In order to simplify the example it is also assumed that the transmission order is not circularly shifted in the next DPPP. During the RTDP of polling round n, the PC sends a data frame piggybacking on a CF-GACK to station 1 since it has received two data frames sent by the station in the previous DPPP. During the DPPP of round $n+1$, station 1 transmits a data frame piggybacking on a CF-GACK, which indicates to the PC that the number of received frames in the previous RTDP was just one. Station 2 has to retransmit the lost data frame. Station 3, which received a data frame in round n, only transmits a CF-GACK frame since it does not have any frame to transmit. Similar to station 3, the PC only transmits a CF-GACK frame during the RTDP to acknowledge the two data frames received from station 1.

F. Admission Control Algorithm

To prevent the starvation of each AC, we propose an admission control algorithm as shown in Fig. 9. The proposed admission control ensures that each AC can still get its guaranteed minimum transmission period described in Section IV-B. The proposed admission control algorithm can be described as follows. To transmit a new traffic stream i, a wireless station sends a request to the PC to be added to the polling list. The required parameters about the traffic in the association request are:

- Mean bit rate (ρ_i): Average bit rate for transmitting frames of stream i (in bit per second).
- User priority: Priority to be used for the transmission of stream i.
- Nominal MSDU size (L_i): Nominal frame size of stream i (in bit).

Upon receipt of the information, the PC calculates the current available time in the DPPP (T_{DPPP}) in the requested AC and if it can support the new stream. The procedure of calculating the available time can be done as follows. First, the PC calculates the number of frames of stream i that would arrive at the mean bit rate during the CFP repetition interval ($T_{CFP_{rep}}$) by using the following equation

$$N_i = \left\lceil \frac{T_{CFP_{rep}} \times \rho_i}{L_i} \right\rceil . \qquad (1)$$

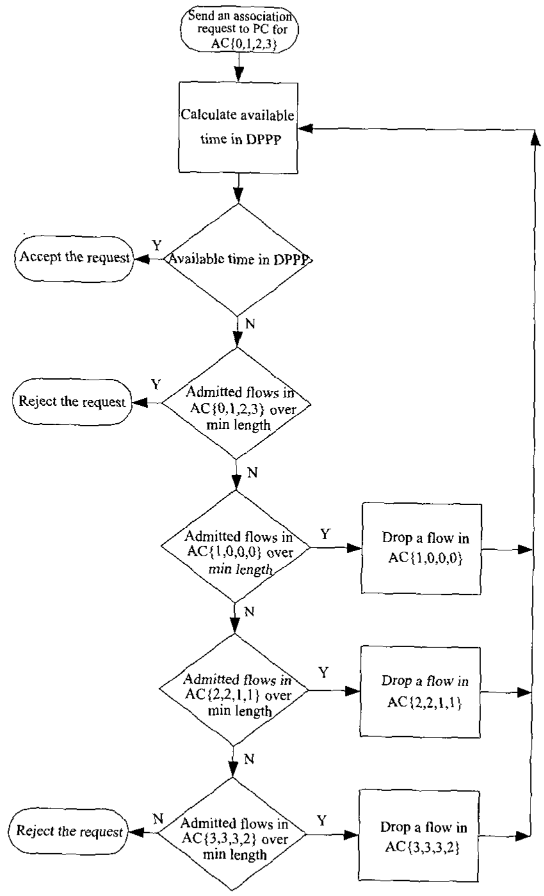

Fig. 9. Diagram of the proposed admission control algorithm.

After calculating N_i, the PC calculates the time used in the DPPP (T_{N_i}) by using the following equation

$$T_{N_i} = \frac{N_i \times L_i}{R} + O \qquad (2)$$

where R is the data rate, and O is the overheads of the MAC sublayer (in time units). Then, the traffic stream i can be admitted if $T_{DPPP} - T_{N_i} > 0$. If the stream can be admitted, the PC would assign a transmission order and a polling ID belonging to the AC for the new admitted stream. After admitting the stream, the PC updates the new available time in the DPPP as $T_{DPPP} = T_{DPPP} - T_{N_i}$. Since a request must be made on a per-flow basis, a station might have a number of transmission orders and polling IDs if it would like to open several sessions of real-time traffic streams. For this reason, a number of transmission queues have to be implemented in each wireless station.

In case the current available time in the DPPP is not sufficient to support the new stream, the PC then checks whether the current transmission period of said AC is over the guaranteed minimum transmission period or not. If the current period was already over the minimum period, the request would be rejected. On the other hand, if the current period was not over, the new stream would be accepted by dropping other admitted streams in an AC whose its current transmission period violates its guaranteed transmission length. The drop of admitted streams in each AC is based on a last-in-first-out (LIFO) basis. Then, the PC recalculates the available time in the DPPP whether it can sup-

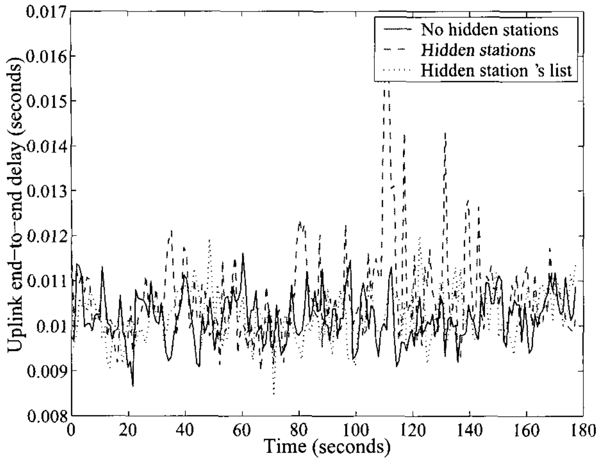

Fig. 10. Uplink end-to-end delay.

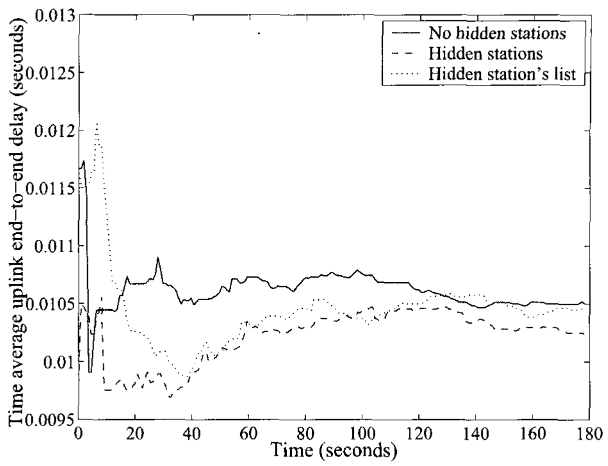

Fig. 11. Time average uplink end-to-end delay of station 5.

port the new stream after an admitted stream of an AC would be dropped. A stream can only be dropped from an AC whose current transmission period is over its guaranteed minimum period. The PC repeats the calculations for new streams until the available time in the DPPP is enough to support the new stream or the current transmission of the said AC is less than its minimum period. If the available time in the DPPP is still not sufficient to support the new stream, the PC then repeats the calculations for the next AC whose current transmission period is over its minimum transmission period. Note that the calculation of available time after dropping an admitted stream is in order of ascending priority of each AC. Finally, if the new steam has been accepted, the PC broadcasts a dropping list to the wireless stations.

V. SIMULATION STUDY OF THE PERFORMANCE OF THE MODIFIED PCF UNDER THE HIDDEN STATION PROBLEM

A. Simulation Scenario

We performed the study in OPNET in order to investigate the effect of the hidden station problem on the performance of the modified PCF in three cases. In the first case, there are no hidden stations in the network. In the second case, the retransmission process after a collision is applied. In the third case, the proposed collision resolution technique is applied.

In the simulation scenario, there were 9 wireless stations transmitting voice traffic through a PC. To emulate a hidden station problem, we assumed that all stations could sense their transmissions except stations 4 and 7 which could not sense transmission of each other as described in the operational example of Section III-D.

Since all wireless stations transmitted voice traffic, the ON-OFF model was used to generate the voice traffic. The average intervals in the ON and OFF state were 1 sec and 1.35 sec, respectively according to Brady's model [13]. A 20-byte voice frame was generated every 25 ms during ON state. The voice frame had 40 bytes of header added. In addition, the CFP repetition interval was set at 20 ms and the CFP maximum duration was set at 5 ms. We also assumed that all stations can send their traffic only in the CFPs.

B. Simulation Results

We selected the uplink end-to-end (ETE) delay during the wireless network as a performance metric of the modified PCF. As illustrated in Fig. 10, which shows the overall uplink ETE delay of the simulating network, the hidden station problem causes higher delay than the case when there are no hidden stations. This is expected as all collided frames have to be retransmitted. Moreover, the retransmission process for the station involved in a collision leads to increased delays for the stations following in the polling sequence. The latter problem can easily be seen in Fig. 11, which shows the time average uplink ETE delay of station 5. Since most of the time the transmissions of station 5 follows the transmissions of station 4, which is one of the hidden stations, its delay mostly suffers due to the retransmission processes of station 4. Therefore, the uplink ETE delay of station 5 increases when compared with the case of no hidden stations.

For the stations that precede station 4 in the polling sequence (e.g., station 3), its delay is not much affected by the retransmission process. This can be confirmed by Fig. 12 which shows that the time average uplink ETE delay of station 3 is quite steady in all three cases.

When the proposed collision resolution technique is applied, the uplink ETE delay of the network is much reduced compared with the case of no hidden stations as also illustrated in Fig. 10. This is because one of the hidden stations (i.e., station 4) is moved to the special list of hidden stations. In addition, the uplink ETE delay of station 5 is noticeably reduced as seen in Fig. 11. This is because station 5 does not have to wait for the retransmission processes of station 4 which has been moved out from the normal polling list and dropped to the special list.

VI. SIMULATION STUDY OF THE PERFORMANCE OF THE MODIFIED PCF WITH PRIORITY SCHEME

A. Simulation Scenario

The simulation of the proposed modified PCF with priority scheme considered three kinds of traffic types: voice, video, and

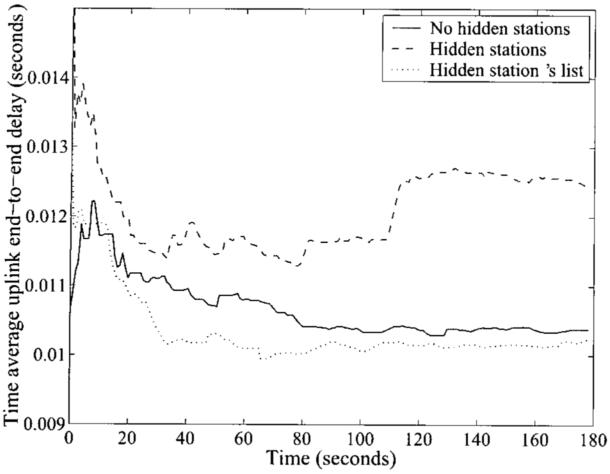

Fig. 12. Time average uplink end-to-end delay of station 3.

data traffic. In the simulation scenario, a number of wireless stations were communicating via a PC with the corresponding number of stations located in a wired network. Each wireless station was assumed to run a single traffic type. Since all traffic in this scenario were considered to be bidirectional, each station was the source of an uplink stream and the sink of a downlink stream.

Since we would like to compare the performance of the proposed priority scheme with the other existing protocols (i.e., the DCF, the EDCA, the PCF, and the modified PCF without support of priority), we investigated the number of stations that can be supported by these protocols without violation of QoS requirements as measurement. In the simulation scenario, we initially set the number of voice stations and video stations each to 10 stations and then varied the number of data stations. Note that we ignored the operation of the admission control algorithm. By investigating the average delay in the wireless network of each traffic type, we could find the number of stations each scheme could support. The number of data stations was increased until either the average delay in both uplink and downlink of the data traffic was higher than 100 ms, or until the average delay of the voice traffic or video traffic in both uplink and downlink was higher than 25 ms.

B. Simulation Traffic Models

Voice traffic: We used the voice traffic model as used in Section V-A.

Video traffic: For the video traffic, we used a trace of a real H.263 video stream from the work in [14]. The average frame size is 319.15 bytes and the average bit rate of a video source was 64 kb/s. The maximum frame size in the network was set to 1500 bytes. Therefore, in the simulation, a generated video frame had the 40-byte header added if the generated frame size was lower than 1460 bytes. In contrast, if a generated video frame size was larger than 1460 bytes, it was fragmented and each fragment had the 40 bytes header added.

Data traffic: For data traffic, we used Source Type 1 as used in an evaluation of the IEEE 802.11e [15]. The model consists of a Poisson distribution generating the following data frame sizes (in byte) and respective probability: (64, 0.6), (128, 0.06), (256, 0.04), (512, 0.02), (1024, 0.25), and (1518, 0.03). The average bit rate of a data source is therefore 200 kb/s. Identical to the video traffic case, fragmentation was used if a generated data size was higher than 1460 bytes and each fragment had the same header size added.

C. Simulation Parameters

The parameters used in the simulation are shown in Table 2. As seen in the table, we used different parameters between the PC and the normal stations in the simulation of the DCF (i.e., CWmin, CWmax, and distributed inter-frame space (DIFS)) and EDCA (i.e., transmission opportunity (TXOP) limit). This is because the PC had to support higher load than the normal stations. Thus, the higher chance to win the contention should be given to the PC.

In the simulation of EDCA, the voice traffic was classified into AC3 and the video traffic was classified into AC2. However, since we would like to give some priority to the data traffic, it was categorized into AC1 instead of AC0.

For the PCF and the modified PCF with/without priority, we assigned 80 percent of the CFP repetition interval to the CFP and the remainder was assigned to the CP. In practice, the remainder period should be enough to transmit the interaction traffic such as association and disassociation between stations and the PC during the CP.

In the simulations of the modified PCF with/without priority support, the header of the forward error correction (FEC) proposed in the previous draft of the IEEE 802.11e (e.g., draft version 3.0) was applied with the sending frames in both protocols.

For all protocols, the buffer size in each wireless station was set to 128 kbytes. The buffer size of the PC, however, was set to 384 kbytes to support higher load than the normal stations.

D. Simulation Assumptions

The followings were made as common assumptions for all protocols in their simulations:

- The wireless medium was error free and the capture effect and the fading effect were ignored. In addition, there were no hidden stations.
- The wired stations were connected to the AP by point-to-point links with negligible delay since we were only interested in the performance of the protocols over the wireless link.
- There was no use of RTS and CTS.
- The location of each wireless station was fixed during the simulation.

The following assumptions were made only for the simulation of the PCF, and the modified PCF with/without priority support:

- Transmission during the CP using the DCF was neglected.
- Every station could transmit its frames only in the CFP.
- A beacon frame was sent only once in the beginning of a CFP per superframe.

We also defined the polling list management used in the simulation for the PCF as follows:

- The PC polled the stations in the polling list according to a simple round robin fashion.

Table 2. Simulation parameters.

Common parameters	Values
Data rates	11 Mb/s
Data rates for control packets and PHY headers	1 Mb/s
MAC overheads	28 bytes
PHY overheads	24 bytes
Beacon body size	35 bytes
SIFS	10 μs
Slot time	20 μs
Simulation duration	3 min

Simulation parameters for DCF	Values
DIFS for normal stations	50 μs
DIFS for PC	30 μs
CWmin for normal stations	31
CWmax for normal stations	1023
CWmin for PC	15
CWmax for PC	31

Simulation parameters for EDCA	Values
AIFS for AC3, AC2, and AC1	50 μs
CWmin for AC1	31
CWmax for AC1	1023
CWmin for AC2	15
CWmax for AC2	31
CWmin for AC3	7
CWmax for AC3	15
TXOP limit for AC1 in normal stations	3 ms
TXOP limit for AC2 in normal stations	6 ms
TXOP limit for AC3 in normal stations	3 ms
TXOP limit for AC1 in PC	6 ms
TXOP limit for AC2 in PC	10 ms
TXOP limit for AC3 in PC	6 ms

Simulation parameters for PCF, modified PCF with/without priority	Values
CFP repetition interval	42 ms
CFP maximum duration	33.6 ms

- If the PC could finish the poll for every station in the polling list within one CFP, the polling sequence for the next CFP would start with the first station in the polling list.
- If the PC could not finish the poll for every station in the polling list within one CFP, however, the polling sequence for the next CFP would start with the next station in the list.
- The polled stations could set the more data subfield in the MAC header of a frame to notify the PC that they still had more frames to transmit. Therefore, if time still remained in the CFP after every station had been polled during one CFP, the PC could continuously poll the stations which had set this bit.
- Although no stations had frames to transmit, the PC could still transmit its buffered frames without piggybacking on a poll.
- The PC could terminate the current CFP if every station had been polled and no more frames were waiting in the buffers of either the stations or the PC.

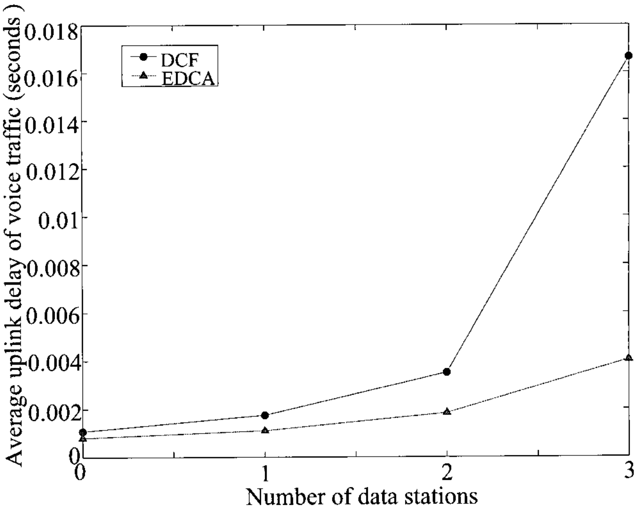

Fig. 13. Comparison of the average uplink delay of voice traffic between the DCF and the EDCA.

E. Simulation Results

E.1 DCF and EDCA

Some simulation results of the DCF and EDCA are shown in Figs. 13 and 14. We concluded from the results that at the initial stage the average delays of all traffic types in the DCF and the EDCA are much lower than that of the other protocols. This is expected, as the wireless stations do not have to wait their rounds to transmit their frames as done in the other schemes.

The DCF can support only 2 data stations because the average delays of voice and video traffic in downlink are much higher than 25 ms when the number of data stations is increased to 3 stations. However, for the uplink direction, the average delays of all traffic types are still below their acceptable values. For the EDCA, it can support 3 data stations since the average delay of the data traffic in both uplink and downlink is higher than 100 ms. For the voice and video traffic in EDCA, their average delays are still below 25 ms since they have higher priority than the data traffic.

E.2 PCF

For the PCF, the results show that it can support 4 data stations since at 5 data stations the average delay of data traffic in both uplink and downlink increases rapidly to much over 100 ms while the delays for the other traffic are still acceptable. The average delays of voice, video, and data traffic of the PCF in the uplink are shown in Figs. 15–17, respectively. Note that the data delay of the PCF becomes too large to be illustrated in the same graph as the previous values when the number of data stations is 5. Since we have not included it in the graph, there is no average delay shown when the number of data stations is 5. The figures show that the average delay of all traffic types in the PCF increase if the number of data stations increases. However, the average uplink delay of voice traffic is steady when the number of data stations is less than 4 stations. The reason is that the

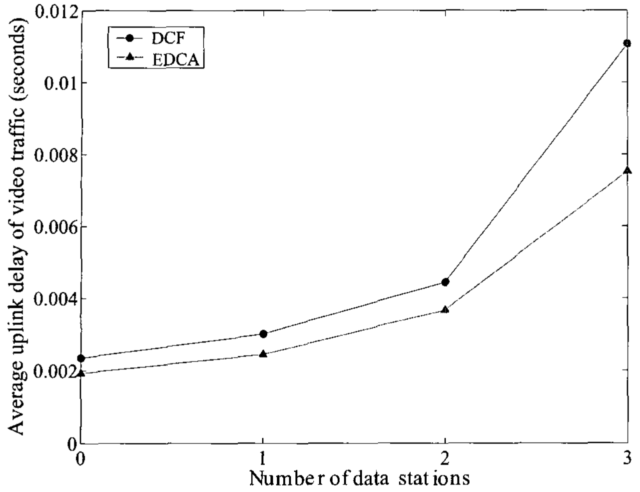

Fig. 14. Comparison of the average uplink delay of video traffic between the DCF and the EDCA.

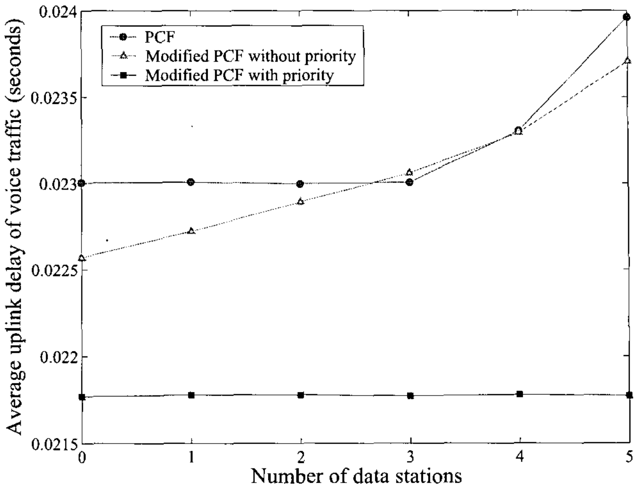

Fig. 15. Comparison of the average uplink delay of voice traffic among the PCF and the modified PCF with/without priority support.

polling sequence of each voice station is constant in each CFP if the capacity in a CFP can still support the amount of data traffic. On the other hand, if the amount of data traffic cannot be supported in a CFP, the polling sequence of each voice station changes. As defined in the PCF polling list management, the station next in turn after a CFP expires is put first in the polling list. This in turns leads to an increment of the average uplink delay of voice traffic when the number of data stations is more than 3 stations. For the video traffic, since the frame size of video traffic is much larger than that of the voice traffic, the increment of data stations greatly affects the average delay of video traffic in the uplink direction as seen in Fig. 16.

The average delay results of all traffic types in the downlink of the PCF are shown in Figs. 18–20. As seen in Figs. 18 and 19, the average delays of voice and video traffic decreases with increasing number of data stations. Recall that the PC could end a CFP if there are no more buffered frames both in the PC and wireless stations. Thus, the frames that arrive after the termination of a previous CFP have to wait for the next CFP. In other words, the increment of data stations yields a longer transmission period in a CFP. Therefore, frames in the PC get a higher probability to be transmitted and the average delays decrease. However, if the number of data stations is increased too much to be supported in a CFP, the average delays of all traffics will rise since the frames buffered in the PC have to wait for the frames ahead in the buffer to be transmitted. That is why the average delays of voice and video traffic increase when the number of data stations is at 4.

E.3 The Modified PCF without Priority Scheme

The number of data stations that can be supported in the modified PCF without support of priority is 5 since the average delay of data traffic in the uplink becomes much higher than 100 ms at 6 data stations. As in the PCF case, the average delays of all traffic types in the uplink increase with varying number of data stations. However, the average uplink delay for voice traffic is not constant as in the case of the standard PCF when the number of data stations is less than 4. This is because the polling sequence in the modified PCF is always shifted in the next round. Therefore, the increment of data stations has an effect on the average uplink delay of voice traffic. For the video traffic, the average uplink delay is much lower than that of the standard PCF since, unlike the standard method, video stations do not have to wait for other stations poll frames. This leads to video stations in the modified PCF accessing the channel faster than video stations in the standard PCF.

In the downlink direction, the average delays of all traffic types decrease when the number of data stations is 1–4 after which they increase. The reason is explained in Section VI-E.2 of the PCF.

E.4 The Modified PCF with Priority Scheme

The modified PCF with support of priority can support the same number of data stations as the modified PCF without priority support. However, the average delays of the voice and video traffic in uplink of the priority scheme are quite steady with a varying number of data stations. This is because the voice and video traffic have their own transmission periods; thus, the increment of the data stations does not affect them.

For the downlink, the average delays of voice and video traffic decrease when the number of data stations vary for the same reason as explained in Section VI-E.2 of the PCF. However, the average delay of data traffic is higher than that of the modified PCF without priority support. This is because of the priority queuing scheme applied in the downlink transmission.

E.5 Analysis of the Results

Although the average delays of the DCF and the EDCA are much lower than that of the other protocols, they can support lower number of data stations compared to the others. This highlights that the DCF and the EDCA are not suitable for controlling the transmission of real-time traffic in an infrastructure wireless network during high loads. On the other hand, the PCF can support higher number of data stations than the DCF and the EDCA as expected since it is designed to control the transmission in the infrastructure network. However, the PCF still

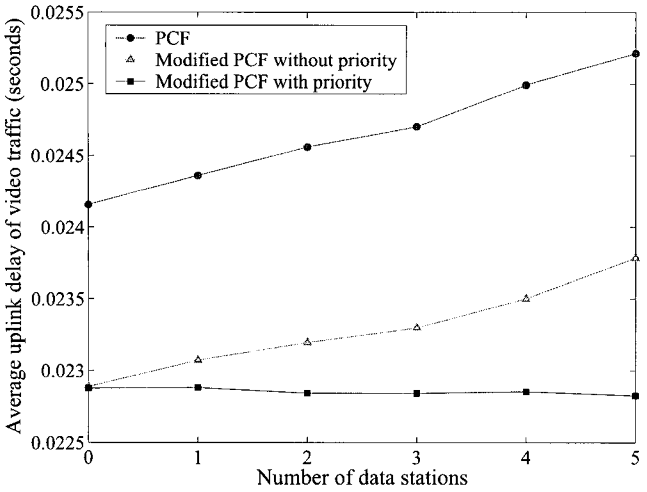

Fig. 16. Comparison of the average uplink delay of video traffic among the PCF and the modified PCF with/without priority support.

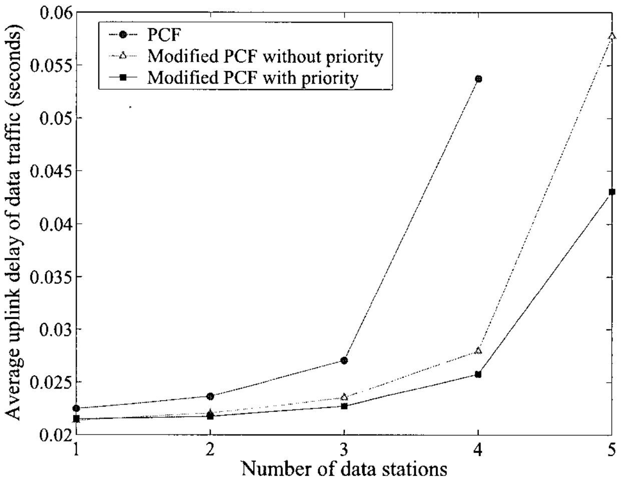

Fig. 17. Comparison of the average uplink delay of data traffic among the PCF and the modified PCF with/without priority support.

supports lower number of data stations than the modified PCF with/without priority support.

Except the DCF and EDCA, the modified PCF with priority support provides the lowest average delays for all traffic types in the uplink since the traffic types have their own transmission periods. The average delay of voice and video traffic in the downlink of the PCF are lower than that of the modified PCF with/without priority support since in the PCF, the PC can transmit whenever it has waiting frames. However, in the modified PCF with/without priority support, the PC has to wait for the RTDP. When comparing the average delays of voice and video traffic in the downlink between the modified PCF with and without priority support, the average delay in the modified PCF with priority support is significantly lower since the voice and video frames can be transmitted before the data frames due to the priority queuing scheme used in the downlink transmission. Although the average delay of data traffic in the downlink of the modified PCF with priority support is higher than that of the modified PCF without priority support, the difference between the delays of the two protocols is not significant.

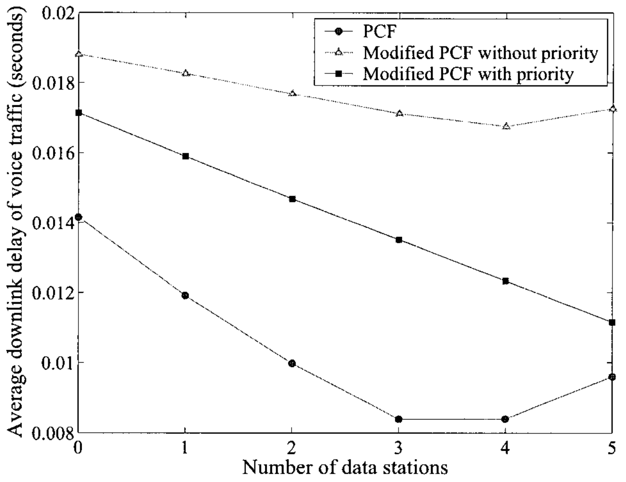

Fig. 18. Comparison of the average downlink delay of voice traffic among the PCF and the modified PCF with/without priority support.

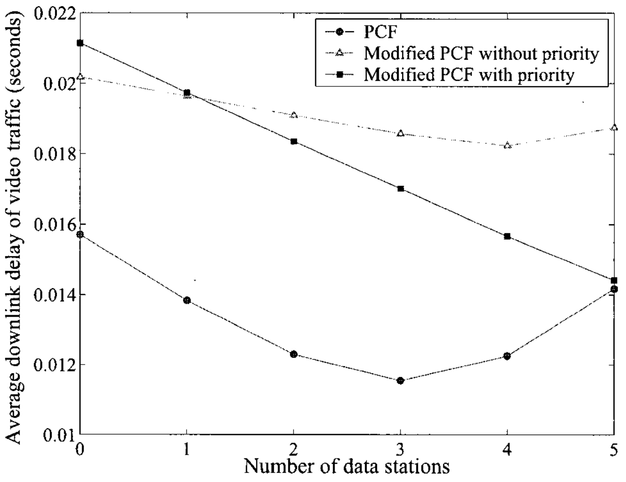

Fig. 19. Comparison of the average downlink delay of video traffic among the PCF and the modified PCF with/without priority support.

VII. CONCLUSION

Since in the modified PCF the wireless stations have to monitor the status of the channel before their transmissions, frame collisions might occur in the channel if there are hidden stations. A retransmission process has been proposed to allow the frames involved in collisions to be retransmitted. We also have proposed a collision resolution mechanism to reduce the probability of collisions due to the hidden station problem.

An investigation of the hidden station problem on the performance of the modified PCF is exposed in this paper. The simulation results show that the hidden station problem increases the overall end-to-end delay of the simulating network. In addition, the delay of the station whose transmission follows a hidden station (i.e., station 5 in the simulation) obviously increases due to the retransmission process. Using a collision resolution, a station presumed to be a hidden station is moved to a list of hidden stations. Our simulation results show that, the efficiencies of both network and station 5 in terms of delay can be significantly

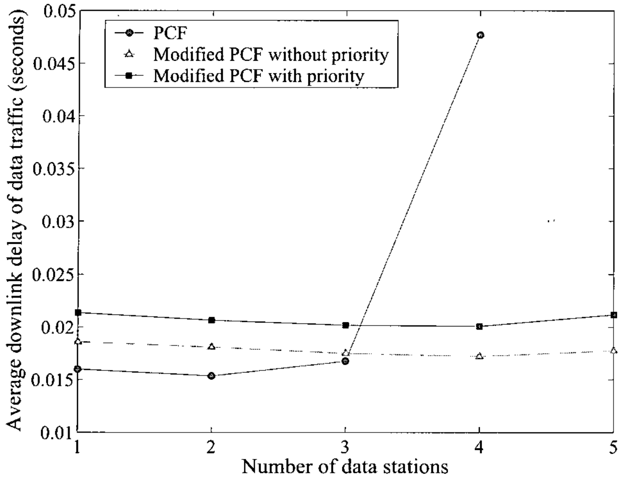

Fig. 20. Comparison of the average downlink delay of data traffic among the PCF and the modified PCF with/without priority support.

improved.

The modified PCF is intended not only to improve the channel utilization over the standard PCF but also to provide better QoS to different real-time traffic types than the standard one. We have therefore introduced a priority scheme to work with the modified PCF. The priority scheme can differentiate different types of traffic such as voice, video, and real-time data traffic. By separating the transmission periods for different traffic types, priority can be given to each AC. An admission control algorithm that guarantees a minimum transmission period of each AC is also proposed to work with the priority scheme.

The performance of the proposed priority scheme is investigated through simulations. By fixing the number of voice and video stations and varying the number of data stations, a judgment in the comparison between the proposed priority scheme and the previously proposed DCF, EDCA, PCF, and the modified PCF without priority scheme were made. The simulation results show that in a given scenario the modified PCF with priority scheme can support a higher number of data stations than the DCF, the EDCA, and the PCF. Although the modified PCF with/without priority scheme can support an equal number of data stations, it is clearly seen from the results that the average delays during high loads of the voice and video traffic in both uplink and downlink transmission of the priority scheme are lower. This means that the modified PCF with priority scheme outperforms the modified PCF without priority scheme in terms of QoS.

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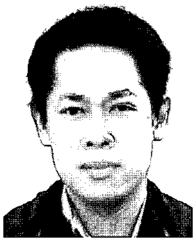

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