Two-Step Multipolling MAC Protocol for Wireless LANs

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***Abstract*—The IEEE 802.11 standard defines two coordination functions: distributed coordination function (DCF) and point coordination function (PCF). These coordination functions coordinate the shared wireless medium. The PCF uses a centralized polling-based channel access method to support time-bounded services. To design an efficient polling scheme, the point coordinator (PC) needs to obtain information about the current transmission status and channel condition for each station. To reduce overhead caused by polling frames, it is better to poll all stations using one polling frame containing the transmission schedule. In this paper, we propose an efficient polling scheme, referred to as two-step multipolling (TS-MP), for the PCF in wireless local area networks (WLANs). In this new scheme, we propose to use two multipolling frames with different purposes. The first frame is broadcast to collect information such as the numbers of pending frames and the physical-layer transmission rates for the communication links among all stations. The second frame contains a polling sequence for data transmissions designed based on the collected information. This frame is broadcast to all stations. Extensive simulation studies show that TS-MP not only overcomes the aforementioned deficiencies, but also help to implement rate adaptation over time-varying wireless channel.**

***Index Terms*— Multipolling (MP), point coordination function (PCF), rate-adaptive medium access control (MAC), wireless local area network (WLAN).**

I. Introduction

IEEE 802.11 wireless local area network (WLAN) has been designed to support portable computing devices using broadband wireless access in both businesses and homes. As broadband technology recently becomes widely available and the demand for the next level of broadband functionality accelerates, WLAN has emerged as a leading technology to satisfy this demand. As a consequence, the IEEE 802.11 standard has been rapidly evolved from 802.11a to 802.11n. Starting from the 2 Mb/s data rate in the physical layer, the data rate of 54 Mb/s has been achieved. More recently, IEEE 802.11n targets to even achieve higher data rate of at least 100 Mb/s in the near future [1].

The medium access control (MAC) protocol in IEEE 802.11 [2] consists of two coordination functions: distributed coordination function (DCF) and point coordination function (PCF). In the DCF, a set of wireless stations (STAs) communicate directly with each other using a contention-based channel access method. In the PCF, the channel access of each station is controlled by polling from a point coordinator (PC) at the access point (AC). While the DCF is designed for the asynchronous data transmission, the PCF is mainly intended to provide time-bounded services such as voice and video. The DCF and PCF can coexist by alternating contention free period (CFP) ruled by PCF and contention period (CP) ruled by DCF.

As the capacity of WLAN increases, it is also important to improve the *quality-of-service* (QoS) for real-time multimedia applications. Since the controlled channel access can reduce the time wasted for accessing the channel during the backoff process in the DCF, the PCF is an appropriate scheme for applications with QoS requirement in WLANs. However, in IEEE 802.11 MAC, the scheduling algorithm for a polling sequence is based on the round-robin (RR) scheme, which is not suitable to handle real-time applications with various QoS requirements. Furthermore, the polling scheme in the PCF introduces significant overhead. The overhead increases the transmission delays on time-bounded traffics and wastes the scarce wireless channel bandwidth. The overhead is caused not only by the polling frames themselves (since one polling frame polls only one station at a time), but also by polling the stations with no frame to transmit. Consequently, most studies on the PCF in WLAN [4]–[12] have been focused on these two factors: the scheduling scheme and the overheads. The scheduling schemes in [4]–[6] are proposed to support multimedia services. In these schemes, all traffic types are differentiated by priorities and the polling sequence is scheduled according to the priorities of the traffics. To reduce the overhead caused by the polling frames, multipolling schemes are proposed in [7]–[9]. The idea is to poll all stations in one shot by one polling frame instead of polling one station at a time. As a consequence, the overheads due to the polling frames can be reduced. The protocols in [10] and [11] target to reduce the unnecessary polling frames used for stations with no pending frames to transmit based on statistical estimation of the traffic characteristic or information reported by a station during the CP. In [12], further performance improvement is achieved by simply removing an acknowledgment (ACK) frame

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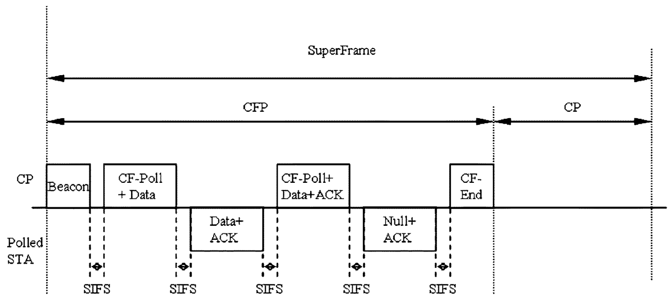


Fig. 1. Channel access of IEEE 802.11 PCF during CFP.

in the PCF. Recently, the IEEE 802.11e Task Group (TG) proposes an enhanced function, namely, the *hybrid coordination function* (HCF) [3], to support the QoS services. In the HCF, the PC is allowed to start the CFP at any time during the CP and the channel access in the CFP is controlled by the polling method in IEEE 802.11.

However, most proposed polling algorithms only consider a constant physical transmission rate. Since a typical wireless channel is time-varying and most wireless networks support several different data rates in the physical layer, an efficient communication system can be designed by selecting the data rate according to the channel condition as proposed in [13]–[15]. Nevertheless, the rate-adaptive polling-based MAC protocol for WLANs has not been investigated yet.

In this paper, we propose an efficient polling-based MAC protocol, *two-step multipolling* (TS-MP), to support real-time applications in a centralized WLAN. In this protocol, we use two multipolling frames with different purposes. The first multipolling frame is sent to collect information such as the number of pending frames at each station and the physical transmission rate of each communication link. Based on such information, the PC schedules a polling sequence for data transmission and the sequence is then broadcast in the second multipolling frame. The proposed protocol not only overcomes the deficiencies of MAC protocol in IEEE802.11, but also helps to implement rate adaptation for a polling-based MAC protocol.

The rest of this paper is organized as follows. Section II reviews the protocols for the CFP in the IEEE 802.11 and 802.11e standards and some known MP schemes. The proposed TS-MP protocol with an efficient scheduling algorithm is presented in Section III. Section IV describes the simulation environment under which the performance of the proposed protocol is evaluated. In Section V, conclusions are provided.

II. Preliminaries

A. Point Coordination Function (PCF) of IEEE 802. 11 MAC

IEEE 802.11 MAC defines a superframe structure, as shown in Fig. 1. The superframe consists of two time periods: CFP and CP. During the CFP, medium access is controlled by the PCF. The CFP begins with a beacon frame containing parameters needed to control the superframe. The protocol used in the PCF in IEEE 802.11 MAC is based on a polling scheme controlled by a PC in such a way that contention free (CF) transmission is guaranteed. The PC keeps the list of stations registered in its basic service set (BSS), which is the set of stations controlled by the PC. Each station can transmit its frame only when it is polled by the PC. The transmissions of frames in the PCF are shown in Fig. 1. The PC polls one station at a time. Hereafter, the polling scheme used in the PCF is called *contention free single polling* (CF-SP). When the PC itself has a pending data frame to the station to be polled, it transmits the data frame by piggybacking it into the polling frame. Moreover, if the PC needs to acknowledge a previously received frame, an ACK frame is also combined with the piggybacked polling frame. When the station receiving the frame from the PC has a pending frame, the data and ACK frames are similarly combined by piggybacking and transmitted back to the PC. When all stations in the polling list are polled or the CFP expires according to *aCFPMaxDuration* defined in the beacon frame, the PC sends a specific control frame, called CF end frame, to signal the end of the CFP. There is a short interframe space (SIFS) idle time between two consecutive frame transmissions in the CFP.

By reducing time consumption due to contention, the PCF is capable of supporting time-bounded services. However, for QoS provisioning, the following problems may arise.

1) The low throughput due to overhead induced by the polling frames.
2) The inefficient RR scheduling algorithm.
3) Lack of information such as the current number of pending frames in a station and the data rate in the physical layer with respect to the channel conditions.
4) Potential collisions caused by stations in a neighboring BSS.
5) The unpredictable transmission time of a polled station.

B. CFP Using Hybrid Coordination Function (HCF) in IEEE 802.11e MAC

The IEEE 802.11e TG proposes some enhancements to overcome the problems 4 and 5, as mentioned in Section II-A. The HCF proposed by the IEEE 802.11e TG controls transmissions of stations in the CFP, as well as in the CP. The HCF in the CFP uses the CF-SP scheme in the PCF with two enhancements. The first one is the use of RTS/CTS handshaking between two communication stations, as defined in the DCF of IEEE 802.11 MAC. The exchange of RTS and CTS frames is performed after a station is polled and before data frame transmission is started. The stations overhearing the RTS or CTS frame in a neighboring BSS set their network allocation vector (NAV) to the value in the ready-to-send (RTS) or clear-to-send (CTS) frame, and will not transmit during the time specified by the NAV. As a consequence, the polled station can transmit its data frame free of collision caused by stations in neighboring BSS.

The second enhancement is the use of transmission opportunity (TXOP). TXOP is the maximum time duration in which a polled station can transmit its frames. If at a polled station, the physical transmission rate is low and a pending frame size is long, the transmission time of the polled station will occupy a large portion of the CFP. For instance, according to the IEEE 802.11 standard, the maximum frame size is 2304 bytes and the lowest data rate in the physical layer is 1 Mb/s. In this case, the transmission time can be more than 20 ms. This long transmission time will reduce the number of stations that can be polled during the remaining time in the CFP. In the HCF, each station is assigned with a TXOP to prevent the transmission of any station from dominating the CFP.

C. Multipolling (MP) Schemes

Although the IEEE 802.11e TG enhances the polling scheme to mitigate some problems of the PCF, other problems, such as 1 to 3 in Section II-A, still remain unaddressed. A number of MP schemes have been proposed to reduce the overhead due to the polling frames in [7]–[9]. The first proposed MP scheme is contention free multipolling (CF-MP) in [7]. In this scheme, the PC sends a MP frame with a polling sequence and time duration assigned to each station for frame transmissions after the beacon frame in the CFP. However, if a polled station does not have enough pending frames to utilize the assigned time duration, the remaining time is wasted. The polling scheme in [8] focuses on the case when a polled station fails to receive a MP frame from the PC. To increase the reliability of receiving the polling information for all stations, each station sends its data frame appending the polling information. In this way, a station that fails to receive a MP frame from the PC has chance to obtain the polling information from the transmissions of other stations. Of course, this introduces additional overhead due to the redundant polling information.

Contention period multipolling (CP-MP) proposed recently in [9] applies the channel access scheme in the DCF of IEEE 802.11 to the PCF. After broadcasting the beacon frame, the PC sends a MP frame containing the transmission sequence, the allocated TXOPs and the initial backoff time for each station. After receiving the polling frame, each station reduces their backoff time, assigned by the PC, by one at a time if the channel is idle during a slot time. When the backoff time of a station reaches zero, the station sends its data frame. In order to avoid collision with the transmission from a station in a neighboring BSS, CP-MP uses RTS/CTS handshaking before a data frame transmission, as in the HCF. It is assumed that all stations can hear or sense transmissions from the PC. However, it is not guaranteed that all stations in the BSS can hear or sense transmissions from all other stations. For instance, when a station cannot sense the transmission of the RTS or CTS frame, it transmits its data frame after its backoff time expires and this leads to collision. For the stations experiencing collision, the PC polls them using the CF-SP scheme after the last station in the polling sequence finishes its transmission. This time period is named recovery phase.

III. Two-Step Multipolling (TS-MP) Scheme

A. Motivation

In the previous section, we present the problems of polling scheme in IEEE 802.11 MAC and some enhanced polling schemes to overcome these problems. Unfortunately, some of these schemes may actually aggravate some of the problems mentioned before. While the polling schemes in the HCF and the CP-MP scheme do solve the collision problem caused by a station in a neighboring BSS, but introduce more overheads due to the RTS/CTS exchanges. In addition, while the CP-MP scheme reduces the overhead due to the polling frames, it may introduce collision between stations even in the same BSS. Moreover, the scheduling scheme for the polling sequence and the TXOP allocation is not clearly specified in any of the aforementioned polling schemes.

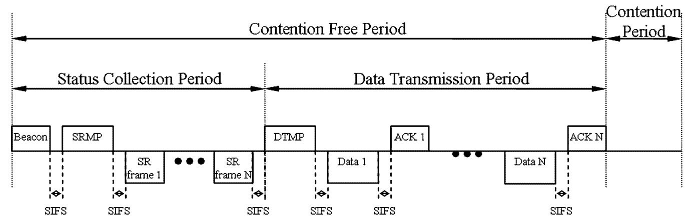


Fig. 2. Time line of TS-MP protocol during CFP.

Finally, the rate adaptation in the CFP has not been incorporated into the aforementioned schemes. Many rate-adaptive MAC protocols for wireless networks have been proposed [13]–[15] to adapt to time-varying wireless channels. However, while the effect of the rate adaptation in the PCF is evaluated in [16], there are no rate-adaptive MAC protocols for the PCF proposed in the current literature.

With these considerations, we introduce a new polling-based MAC protocol in the next subsection and show how the proposed protocol can overcome the problems discussed in Section II-A.

B. Two-Step Multipolling (TS-MP)

We observe that in the current polling schemes, the PC must poll all stations regardless of whether a station has pending frames or not because the PC does not have any knowledge about the buffer status of each station. If the PC knows the buffer status of each station, a station without any pending frame should not be polled. In addition, when the physical transmission rate for each communication link is known, the PC can estimate the channel access time for each station, which helps to determine the TXOP for the station.

We refer to the proposed MP scheme as TS-MP. Using TS-MP, the PC can obtain information from each station in every CFP. Utilizing this information, the PC efficiently schedules the polling sequence and assigns TXOPs to stations. In addition to reducing the overheads caused by polling frames, TS-MP can prevent a collision from a transmission of neighboring station without creating additional overheads such as a RTS/CTS handshaking. Furthermore, TS-MP also achieves a rate adaptation based on channel condition.

Fig. 2 illustrates the operation of the proposed TS-MP MAC protocol. The CFP period is divided into two subperiods: status collection period (SCP) and data transmission period (DTP). A detailed operational description of these periods will be given in the following sections.

1) Status Collection Period (SCP): After broadcasting the beacon frame at the beginning of the CFP, the PC transmits the first MP frame, called *status-request multipoll* (SRMP), to collect information from each station. Fig. 3(a) shows the frame structure for the SRMP, whose length varies with the number of stations to be polled. The *polling count* subfield indicates the number of stations to be polled and the *AID* subfield is an association identifier, which identifies a station

Byte : 2	6	1	2		2	4
Frame Control	BSSID	Polling Count (N)	AID 1	● ● ●	AID N	FCS

(a)

Byte : 2	6	2	1	2	4
Frame Control	BSSID	Tentative NAV	Buffer Status	AID	FCS

(b)

Byte : 2	6	1	5 x Polling Count (N)			4
Frame Control	BSSID	Polling Count (N)	Polling Control			FCS
			AID (2bytes)	Rate (1byte)	TXOP (2bytes)	

(c)

Fig. 3. Frame structures. (a) SRMP frame. (b) SR frame. (c) DTMP frame.

Current Rate (4 bits)	Downlink Rate (4 bits)

Signal (8 bits)	Service (8 bits)	Length (16 bits)	CRC (16 bits)

Fig. 4. PLCP header format for TS-MP.

in the BSS. The stations to be polled are selected by the first scheduling scheme explained in Section III-C. Each station polled by the SRMP frame sends a status-response (SR) frame back to the PC with some status information. Fig. 3(b) shows the frame format for the SR frame. Specially added fields in the SR frame are the *tentative-NAV* and *buffer status* fields. The *tentative-NAV* field indicates the tentative time duration used for NAV allocation of stations belonging to a neighboring BSS that hear the transmission of the sender. In order to avoid the collision caused by the transmission of a station in the neighboring BSS, when a station hears a SR frame with different BSSID number, it sets its NAV to the value in the *tentative-NAV* field and does not transmit during the period of its NAV. When the station in a neighboring BSS overhears a data frame from the same station, its NAV value is reset to the value in the *duration* field of the data frame, which indicates the end of the data frame transmission. The value of *tentative-NAV* field may indicate the end of the CFP. If a polled station does not have a frame to transmit in this CFP, the value of the *tentative-NAV* field is set to zero since this station will not be polled for a data frame transmission at the second MP period. The *buffer status* field indicates the number of pending frames in the buffer of a station. This information is important for the PC to schedule a polling sequence and set the TXOP for each station in the incoming data transmission period. Moreover, the information about the pending frames reduces the time loss due to the polling of stations with no pending frames because these stations are removed from the polling sequence for the data transmission.

2) Data Transmission Period (DTP): After receiving the last SR frame, the PC sends a *data transmission multipoll* (DTMP) frame. A polling sequence in the DTMP is constructed by the second scheduler based on the information obtained from the SR frames. The operation of this scheduler will be described in Section III-C. The frame format is illustrated in Fig. 3(c). The *polling count* field is the number of stations to be polled in the DTP. The *polling control* field consists of three subfields: *AID*, *TXOP*, and *rate*. These three subfields specify the ID of a station to be polled, the time duration assigned to a station for transmission of pending frames, and the data rate for uplink frames, respectively. After the PC estimates the channel with the received SR frames in the SCP, a data rate is chosen for the transmission of the polled station. In comparison to the inaccurate TXOP allocations in the HCF and CP-MP, the PC can accurately allocate TXOPs to stations based on the information such as the number of polling frames and the physical transmission rate for these frames, which are obtained from SR frames. Therefore, the wasted time due to the inaccurate allocation of TXOP discussed in Section II is reduced. Each polled station transmits data frames with the given data rate from the DTMP frame after the predecessor's TXOP expires. There is a SIFS idle time between two consecutive TXOPs.

3) Rate Adaptation: To support rate adaptation in the CFP, the physical-layer header is modified as shown in Fig. 4. The *service* field in the physical-layer header is divided into two four-bit subfields, namely, the *current rate* and *downlink rate* subfields. The *current rate* subfield indicates the data rate of the current frame and the *downlink rate* subfield indicates the data rate selected through the channel estimation based on the received SRMP frame at a station. The value in *downlink rate* subfield is used to generate the downlink frame at the PC. For instance, after the PC sends the SRMP frame at the base rate, each polled station estimates the channel and sends the SR frame containing the selected rate in the *downlink rate* subfields back to the PC. The SR frame is transmitted at the base rate. If the PC has a pending frame to transmit, the frame is modulated and coded according to the data rate informed by the SR frame of the destination station. For any frame from the PC, the value of *downlink rate* subfield is set to zero, which does not indicate any data rate because the subfield is used only by the SR frames. The data rates for the uplink data frames are informed by the DTMP frame after the communication links are estimated based on the SR frames at the PC. Using this operation, the physical transmission rate for the uplink and downlink transmissions can be dynamically adjusted according to the current channel condition.

4) An Illustration: Fig. 5 shows a timing diagram to illustrate the operation of the proposed MP MAC protocol. We assume that there are one PC and four real time traffic stations (A, B, C, and D) in the BSS. Station E is a station in a neighboring BSS and can hear the transmission from Station C. In the beginning of the CFP, The PC sends a SRMP frame with the transmission sequence $A \rightarrow B \rightarrow C \rightarrow D$. After the SRMP transmission and SIFS, each station sends a SR frame back to the PC. When Station E hears the SR frame from Station C, it sets its NAV to the value of the *tentative-NAV* field. In this example, it is assumed that station B does not have any frame to transmit. As a consequence, the Station B is removed in the polling sequence in the DTMP frame. All stations except Station B, start to transmit according to the sequence given in the DTMP frame, and their

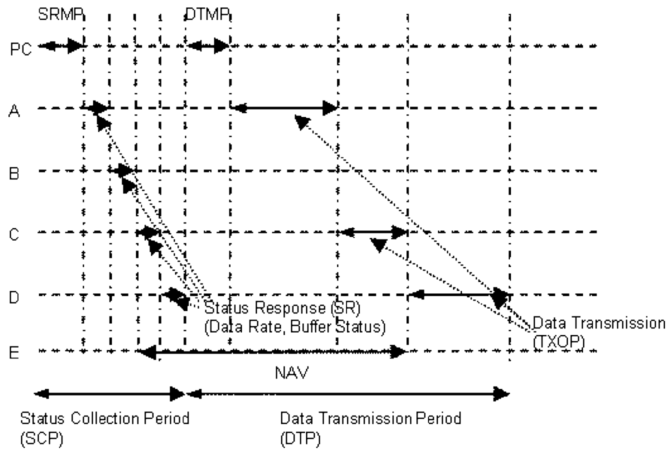


Fig. 5. Example of TS-MP protocol.

physical-layer frames are generated using the data rates specified in the DTMP. When Station E hears the transmission of the data frame from Station C, it resets its NAV to the value of the *duration* field in the MAC header.

C. Polling Scheduler

As mentioned in the previous section, the commonly used scheduling method for the CFP in WLANs is the RR scheme, which is not efficient in dealing with services with various QoS requirements. To design a better scheduling algorithm, the PC needs to have information about the node status and the channel condition before polling all stations. Using the proposed protocol described in Section III-B, the PC is able to obtain information needed for scheduling a polling sequence and as a consequence a better scheduling scheme can be implemented.

Before describing two proposed scheduling schemes, we introduce two main factors that affect the scheduling process The first factor is the service period of Station i, SP_i. The SP_i is the estimated interarrival time of frames at Station i with payload P_i which is given by

$$\mathrm{SP}_i = \left\lfloor \frac{P_i \cdot 8}{M_i \cdot T_{\mathrm{SF}}} \right\rfloor \tag{1}$$

where P_i, M_i, and T_{SF} are the payload in the MAC frame in bytes, the average data arrival rate in the MAC layer at node i, and the time duration of a superframe, respectively. P_i and M_i are obtained from the admission control unit in the PC during the association period. The admission control unit administers policy or regulates the available bandwidth resource [3]. As illustrated in (1), SP_i is expressed in the number of superframes and is also calculated by the scheduler.

We define another parameter n_i related to SP_i in order to manage the polling time of Station i. The polling time will be illustrated in detail in Section III–C1. n_i is initialized to be SP_i and decreased by one every superframe passed until it reaches to one. When n_i becomes one, it is reset to SP_i at the next superframe.

The second factor is E_i, which is the normalized number of transmitted frames during the previous W superframes at Station i. This parameter can be defined as

$$E_i = \frac{\sum_{j=1}^{W} e_i^j}{M_i} \tag{2}$$

where W, *the averaging window size*, is the number of previous superframes to be considered for the averaging, and e_i^j is the number of transmitted frames in the jth superframe at Station i in the averaging window. This parameter is tracked and updated by the PC in every superframe.

1) First Scheduler for SRMP: A scheduler for SRMP is useful for the case when there are many stations to be polled within the limited CFP period. When the number of stations to be polled by SRMP is very large, a large amount of time is spent during SCP, leading to excessive overhead and poor performance of the polling scheme. In order to avoid this situation, the following scheduler for SRMP is proposed.

Step 1) Determine the number of stations to be polled in SRMP.

The number of stations to be polled in the current CFP is determined from the information obtained in the previous CFPs. When the PC experiences a shortage of DTP to poll all stations with frames to transmit in the previous CFP, the number of stations to be polled in SRMP is reduced by one. The number is increased by one when DTP is enough to poll all stations with frames to transmit in the previous CFP. The number of stations to be polled for SRMP in the jth CFP can be expressed as follows:

$$N_j = \begin{cases} N_{j-1} - 1, & \text{if } T_{\mathrm{alloc}}^{j-1} > T_{\mathrm{DTP}}^{j-1} \\ N_{j-1} + 1, & \text{otherwise} \end{cases} \tag{3}$$

where T_{DTP}^{j-1} is the time duration of DTP in the previous CFP and T_{alloc}^{j-1} is the sum of TXOPs estimated for all stations in the previous CFP as follows:

$$T_{\mathrm{alloc}}^{j-1} = \sum_{i=1}^{n} T_{\mathrm{TXOP}}^{i}. \tag{4}$$

In this paper, a step size to decrease or to increase the number of stations to be polled is set to 1.The step size needs to dynamically change according to the networks situations. Finding a value of the step size may be an optimization problem and is, thus, out of scope of this paper.

Step 2) Design the polling sequence.

Once the number of stations to be polled in SRMP is defined, the next process is to select the stations to be polled and to decide the polling sequence. At first, all stations are arranged in the order of n_i, from low to high values. Since a lower value of n_i indicates that Station i has a higher probability of having frames to transmit, the stations with a lower value of n_i are polled with higher priority. The next criterion that decides the polling sequence is E_i. For stations that have the same n_i

value, they will be arranged in an increasing order according to the E_i values. Since E_i represents the average number of transmitted frames during the previous W superframes, to achieve some of fairness, the stations with lower E_i values should have higher priority to be polled. From these two procedures, the polling sequence for all stations in BSS is obtained. The N_j stations in the polling sequence are polled by SRMP.

Step 3) Prioritize different traffics.

Different traffic types can be scheduled in the polling list according to their own priorities. After ordering the polling list, among the stations with the same n_i and E_i values, the one with higher priority traffic should be assigned to the front of the list. For instance, if two stations have the same n_i and E_i values, but have different traffic types, say, CBR and VBR. Assuming that CBR traffic has higher priority than VBR traffic, the station with CBR traffic will be put in the list ahead of that with VBR traffic.

Step 4) Synchronize the polling time instants.

We define the polling time instant as the time instant when a station is polled. Since the lower values of n_i have higher priority in polling sequence, the polling instant is closely related to n_i. Since n_i is obtained from SP_i, the polling instant in the time line is not synchronized with the actual time instant of frame generation. Consequently, we need to adjust the polling instant to minimize the delay. This process is called *synchronization of polling instant*. We define a frame delay, T_d^i, to be the time duration from the time instant when one frame is generated in the MAC layer to the time instant when the frame is transmitted at Station i. When T_d^i is larger than T_{SF}, the PC changes the polling instant by updating n_i as follows:

$$n_i = \begin{cases} \mathrm{SP}_i - 1, & \text{if } T_d^i > \dfrac{(\mathrm{SP}_i \cdot T_{\mathrm{SF}})}{2} \quad \text{and} \quad n_i = 1 \\ \mathrm{SP}_i + 1, & \text{if } T_d^i \le \dfrac{(\mathrm{SP}_i \cdot T_{\mathrm{SF}})}{2} \quad \text{and} \quad n_i = 1 \\ n_i - 1, & \text{if } T_d^i > \dfrac{(\mathrm{SP}_i \cdot T_{\mathrm{SF}})}{2} \quad \text{and} \quad n_i > 1 \\ n_i + 1, & \text{if } T_d^i \le \dfrac{(\mathrm{SP}_i \cdot T_{\mathrm{SF}})}{2} \quad \text{and} \quad n_i > 1 \end{cases}. \tag{5}$$

When the T_d^i is large, decreasing the value of n_i in (5) reduces the frame delay. On the other hand, it may increase the frame delay when the T_d^i is small (but larger than T_{SF}) because reducing n_i by 1 makes a polling instant moves T_{SF} in the front, so that the polling instant for a data transmission can be earlier than the instant of a frame generation. Therefore, instead of reducing the value of n_i, it is increased. It may cause a little delay, but prevents the polling instant from passing the instant of a frame generation.

The PC is not able to know T_d^i for each station, but each station knows T_d^i for its own frames. Thus, each station needs to inform its T_d^i to the PC when T_d^i larger than T_{SF}. For this purpose,

Protocol Version	Type	Subtype	To DS	From DS	More Frag	Retry	Pwr Mgt	More Data	WEP	Order
2	2	4	1	1	1	1	1	1	1	1

Bits :

Fig. 6. Format of frame control field.

the *subtype* subfield in the *frame control* field of the MAC header is used by the uplink frames. Fig. 6 shows the format of the *frame control* field. If the value of T_d^i is larger than $(\mathrm{SP}_i{\cdot}T_{\mathrm{SF}})/2$, the value of the *subtype* subfield is set to 1000. Otherwise, the value of the *subtype* subfield is set to 1001.

2) Second Scheduler for DTMP: From stations polled by SRMP, the PC obtains information such as the data rate in the physical layer and the number of frames in the buffer at the MAC layer. According to this information, the PC allocates a TXOP to each station that has frames to transmit and with value of n_i to be one. The TXOP for Station i is

$$\mathrm{TXOP}_i = \Big(T_{\mathrm{pre}} + T_{\mathrm{PHY\_hdr}} + T_{\mathrm{MAC\_hdr}} + 2 \cdot T_{\mathrm{SIFS}} + T_{\mathrm{ACK}} + \frac{L_{\mathrm{Payload}}}{R}\Big) \cdot Q_i \tag{6}$$

where $T_{\mathrm{pre}}, T_{\mathrm{PHY\_hdr}}, T_{\mathrm{MAC\_hdr}}$, and T_{ACK} are the time durations of the preamble, the PHY header, the MAC header and the ACK frame, respectively. T_{SIFS} is the SIFS idle time. L_i is the length of the payload in bits, R is the data rate in the physical layer, and Q_i is the number of frames in the buffer of Station i. There are two cases we should consider. The first is the case when the remaining time in the CFP after the DTMP frame is less than the sum of TXOPs of all stations with pending frames. The other is the opposite case. For the first case, the scheduler chooses the stations with nonzero Q_i values to be placed at the beginning of the polling list using n_i and E_i, as described in Section III–B1. Then, it sends the DTMP frame with the information, such as TXOP, rate and AID of a selected station. For the second case, more stations are chosen from the polling sequence after N_j stations are chosen until the remaining time in the CFP is filled with their TXOPs. For stations not polled in SCP, but will be polled due to the second case, the Q_i value reported by the station in the previous superframe is used for TXOP allocation.

IV. Performance Evaluation

A. Wireless Channel Model

To reflect the fact that the surrounding environmental clutter may be significantly different for each pair of communication stations with the same distance separation, we use the log-normal shadowing channel model [20]. The path loss $\overline{\mathrm{PL}}$ at distance d is

$$\overline{\mathrm{PL}}(d)[\mathrm{dB}] = \overline{\mathrm{PL}}(d_0)[\mathrm{dB}] + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{7}$$

where d_0 is the close-in reference distance, n is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable (in decibels) with standard deviation σ (in decibels).

We set n to 2.56 and σ to 7.67 according to the result of measurements for a wideband microcell model [20]. To estimate $\overline{\mathrm{PL}}(d_0)$, we use the Friis free space equation

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} \tag{8}$$

where P_t and P_r are the transmit and receive power, G_t and G_r are the antenna gains of the transmitter and receiver, λ is the carrier wavelength, and L is the system loss factor which is set to 1 in our simulation. Most of the simulation parameters are drawn from the data sheet of Cisco 350 client adapter [22]. The received power is

$$P_r(d)[\mathrm{dB}m] = P_t[\mathrm{dB}m] - \overline{\mathrm{PL}}(d). \tag{9}$$

A minimum received power level for the carrier sensing is set to -95 dBm, which is the noise power level. When the received power level is less than -95 dBm, it is considered that the node can neither sense the channel nor demodulate the received frame. Finally, the long-term signal-to-noise ratio (SNR) is

$$\mathrm{SNR}_L[\mathrm{dB}] = P_t - \overline{\mathrm{PL}}(d) - N + \mathrm{PG}[\mathrm{dB}] \tag{10}$$

where N is the noise power set to -95 dBm from [23]. In (10), PG is the spread-spectrum processing gain given by

$$\mathrm{PG}[\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{C}{S}\right) \tag{11}$$

where C is the chip rate and S is the symbol rate. Since each symbol is chipped with an 11-chip pseudonoise (PN) code sequence in the IEEE 802.11 standard, PG is 10.4 dB.

To demonstrate the functionality of the rate adaptation scheme in our proposed protocol, the received SNR_L is varied by the Ricean fading gain α. Under this model, the SNR of the received signal is

$$\mathrm{SNR}[\mathrm{dB}] = 20 \cdot \log_{10}\alpha + \mathrm{SNR}_L[\mathrm{dB}]. \tag{12}$$

In this simulation, all stations are moving around with a slow pedestrian speed of 1 m/s, within the coverage area of the BSS. Herein, it is assumed that the channel is constant during the period of one superframe.

For the data rate in the physical layer for each communication link, we assume that the system adapts the data rate by properly choosing one from a set of modulation schemes according to the channel condition. The set of modulation schemes used in our simulation studies are binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), 16, 64, and 256 quadrature amplitude modulation (QAM). For simplicity, we ignore other common physical layer components such as error correction coding. With 1 MHz symbol rate and the above modulation schemes, the achieved data rates are 1, 2, 4, 6, and 8 Mb/s, respectively. Assuming that the symbol errors within a data frame are independent, the frame error rate (FER) is related to the symbol error rate (SER) by

$$\mathrm{FER} = 1 - (1 - \mathrm{SER})^N \tag{13}$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
CWmin	31
CWmax	1023
SIFS Time	10 us
DIFS Time	50 us
Slot Time	20 us
MAC Header	272 bits
PHY Header	48 bits
Preamble	144 us
ACK frame length	112 bits
RTS frame length	160 bits
CTS frame length	112 bits
aCFPMaxDuration	30 ms
Superframe Duration	32 ms

where N is the number of symbols in the payload of an MAC frame. We set the target FER to 8% according to the IEEE 802.11 standard [1]. The SER equation to determine the SNR are found in [21]. For BPSK

$$\mathrm{SER} = Q\left(\sqrt{\frac{2E_s}{N_0}}\right) \tag{14}$$

and for QPSK and M-ary QAM

$$\mathrm{SER} \le 1 - \left[1 - 2Q\left(\sqrt{\frac{3E_s}{(M-1)N_0}}\right)\right]^2 \tag{15}$$

where E_s/N_0 is the SNR per symbol and M is the signal constellation size. From the SER performance curves calculated from (14) and (15), the SNR ranges for the corresponding modulation schemes that the target SER is satisfied are given as follows:

$$R = \begin{cases} 1\ (\mathrm{BPSK}), & \mathrm{SNR} < \mathrm{SNR}_2 \\ 2\ (\mathrm{QPSK}), & \mathrm{SNR}_2 \le \mathrm{SNR} < \mathrm{SNR}_4 \\ 4\ (16\mathrm{QAM}), & \mathrm{SNR}_4 \le \mathrm{SNR} < \mathrm{SNR}_6 \\ 6\ (64\mathrm{QAM}), & \mathrm{SNR}_6 \le \mathrm{SNR} < \mathrm{SNR}_8 \\ 8\ (256\mathrm{QAM}), & \mathrm{SNR}_8 \le \mathrm{SNR} \end{cases} \tag{16}$$

where SNR_i is the SNR threshold for the data rate i to meet the target SER.

B. Network Setting

We assume that all stations except for the PC are uniformly distributed in the coverage area of an independent BSS with diameter 250 m. The PC is always located at the center of the area. Since the proposed protocol and the other comparative protocols all have mechanisms to avoid collisions with stations in the neighboring BSS, we do not consider any neighboring BSS in this simulation. Moreover, only uplink traffic is considered. The synchronization problem with a preamble and the propagation delay are not considered in our simulation. The parameters used in this simulation study are shown in Table I. The choice of these parameters is based on the IEEE 802.11b DSSS standards. The duration of the CFP varies depending on the number of stations. If there is residual time in a CFP after all stations are polled or the PC broadcasts a CF-end frame, the residual time of CFP is merged with the CP. At least 4% of the superframe duration is assigned to the CP [1], [6]. Since the PCF is designed for the time-bounded services, we study two real-time traffic types, CBR and VBR, in the simulation. The traffic models for these traffic types are described as follows.

- CBR voice traffic model.

  A voice source has two states, talkspurt and silence. Talkspurt is characterized by a voice activity detector (VAD) [17]. The durations of talkspurt and silence are exponentially distributed with mean values of t_1 and t_2, respectively. The values of t_1 and t_2 are set to 1.0 and 1.35 s, respectively. We use a 16 kb/s voice traffic source to generate one 200 bytes payload voice frame every 0.1 s during the talkspurt period. We assign the delay time limit of a voice frame to 0.1 s. That is, all voice frames must be transmitted before the next frame arrives.
- VBR MPEG-4 traffic model.

  In our simulation, the trace statistics of actual MPEG-4 video streams reported in [18] and [19] are used. We use the video stream of Star Wars IV, which has a mean bit rate of 53 kb/s and a peak rate of 940 kb/s. The size of video packet is set to 800 bytes based on [9]. According to the mean bit rate of 53 kb/s, the delay limit of video packet is set to 0.12 s. We assume that each station has sufficient buffer size, so that frames generated at the higher bit rate than mean rate are stored in the buffer.

Each station has either one CBR or one VBR flow. In this simulation, three measurements for performance evaluation are considered: dropping probability, average delay, and CFP throughput. The average delay is defined as the time duration from the arrival of a frame in the MAC layer to the departure of the frame. It is assumed that the instant that a frame is generated is the same as that of the frame arrival in the MAC layer. The CFP throughput is

$$\text{Throughpt}_{\text{CFP}} = \frac{\sum_{j=1}^{N_{\text{SF}}} \sum_{i=1}^{N_{\text{STA}}} \text{Data}_i^j}{\sum_{j=1}^{N_{\text{SF}}} T_{\text{CFP}}^j} \tag{17}$$

where $T_{\text{CFP}}^j, N_{\text{SF}}, N_{\text{STA}}$, and Data_i^j are the used CFP duration in jth superframe, the total number of superframes, the number of stations and the transmitted data bits at station i in the jth superframe, respectively.

We simulate 200 different realizations with different positions of stations. Each scenario is simulated for 60 s. In every realization, the channel condition for each communication link is recalculated according to the distance between any two stations and the shadowing environment for each station.

C. Performance Comparison With Round-Robin (RR) Scheduling Scheme

In this section, we compare the performance of two existing protocols with that of our proposed protocol. The first protocol is the CF-SP scheme with RTS/CTS frames in 802.11e and the second protocol is CP-MP. To evaluate the efficiencies of these two protocols and simplify the simulations, a RR scheduling scheme is used for all protocols. For the same purpose, it is assumed that the channel is constant during a simulation of one realization, and the physical transmission rate of each communication link is selected via the rate decision process described in Section IV-A. These assumptions for the channel and the rate are also applied to Section IV-D.

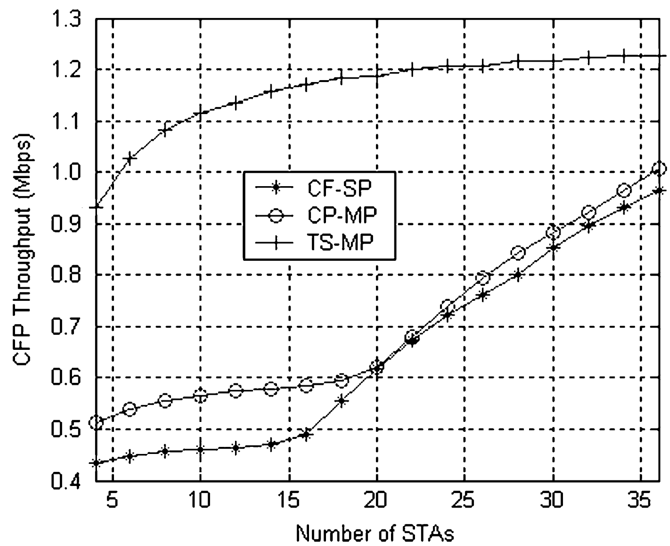
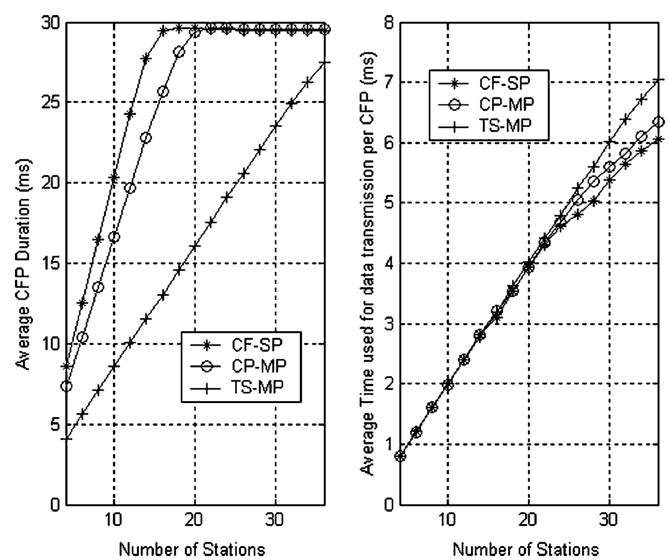


Fig. 7. Average CFP throughputs.



(a) (b)

Fig. 8. (a) Average CFP duration. (b) Average time used for data transmissions.

Fig. 7 shows the CFP throughputs of the three protocols when stations with CBR traffic and stations with VBR traffic coexist in the BSS. The number of stations with CBR traffic is the same as that with VBR traffic. The performance of TS-MP is 18%–140% higher than that of CF-SP and 13%–100% higher than that of CP-MP. However, we observe that the CFP throughputs of CF-SP and CP-MP increase rapidly after a certain number of stations, 18 for CF-SP and 22 for CP-MP.

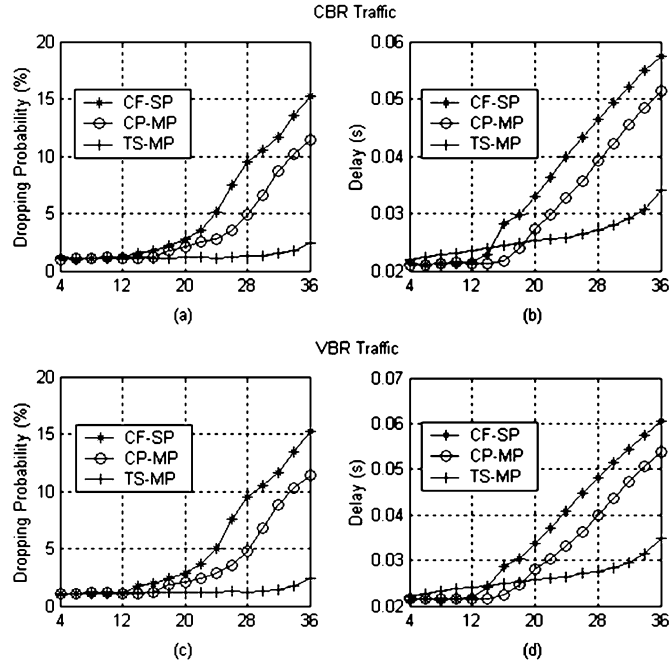


Fig. 9. Dropping probability and average delay as functions of the number of stations.

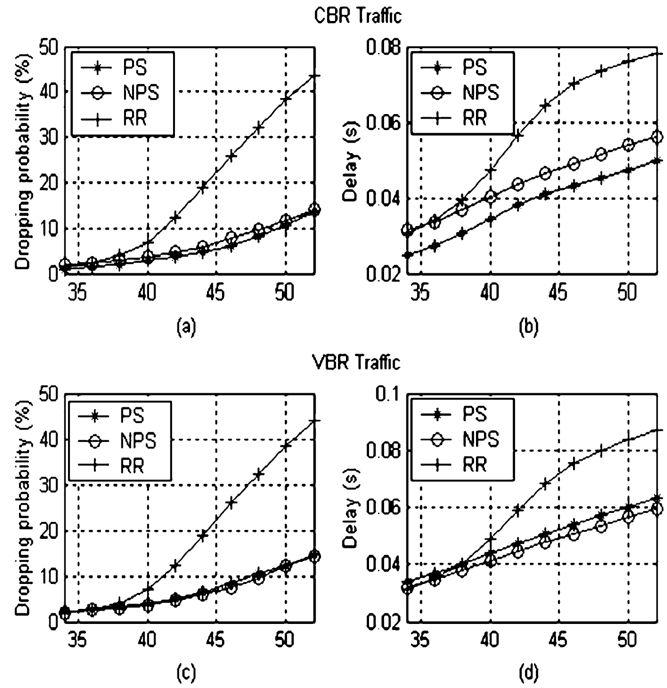


Fig. 10. Dropping probabilities and average frame delays of the three configurations.

This is elucidated through the analyses of Fig. 8(a) and (b). Fig. 8(a) shows the average CFP duration in a simulation, and Fig. 8(b) shows the average time used for data transmissions, which is the MAC payload, in a CFP. The average CFP duration increases rapidly in CF-SP and CP-MP comparing to that in TS-MP. In addition, it is saturated at 18 stations for CF-SP and 22 for CP-MP since the maximum CFP duration is constrained in Table I. However, in Fig. 8(b), the results for the time used for the data transmission are not distinguishable for three protocols. This indicates that CF-SP and CP-MP require more time for serving the same number of stations than TS-MP does. That is, the time consumed by the overheads in CF-SP and CP-MP in the CFP is much more than that in TS-MP as described in Section III. Therefore, the CFP duration in CF-SP and CP-MP reaches *aCFPMaxDuration* earlier than that in TS-MP. The rapid increase in the CFP throughputs for CF-SP and CP-MP is elucidated by the saturation of the CFP. Fig. 9(a) and (c) shows the dropping probabilities, and Fig. 9(b) and (d) shows the average frame delays for the CBR and VBR traffic. As the number of stations increases, the dropping probabilities of TS-MP reduces up to 87% of that of CF-SP and 80% of that of CP-MP for both traffic types. However, we observe that the average delay of TS-MP with a small number of stations is larger than those of the other protocols. This is caused by SCP in TS-MP. In each CFP, the first data frame in TS-MP is transmitted after the transmission of the DTMP frame. That is, most of the overhead in TS-MP is placed in the front of the CFP, whilst the overhead is distributed to each data frame transmission in CF-SP and CP-MP. Therefore, when the number of stations is small, the delay due to the overhead of the TS-MP protocol appears prominently. However, as the number of stations increases, all stations in CF-SP and CP-MP cannot be served during current CFP because the required time to serve all stations passes over the maximum CFP duration as explained previously with Fig. 8. Thus, some of the stations are polled in the next CFP, which causes an additional delay. On the other hand, in TS-MP, most of stations are served in the current CFP so that the delay increases slowly, as shown in Fig. 9(c) and (d).

D. Performance Evaluation With the Proposed Scheduling Scheme

In the previous section, simulation results show that the proposed protocol provides better performance than the other two protocols. Now, we evaluate the performance of the proposed protocol with the proposed scheduling scheme. In this section, three configurations are compared.

Case 1) TS-MP with RR scheduling.
Case 2) TS-MP with the proposed nonpriority-based scheduling (NPS).
Case 3) TS-MP with the proposed priority-based scheduling (PS).

In our simulation, the CBR traffic has higher priority than the VBR traffic. The number of stations in the BSS increases from 34 to 52 with a step size 2, and the number of stations with CBR traffic is the same as the number of stations with VBR traffic.

As shown in Fig. 10, the frame dropping probability of Case 2) for CBR traffic and VBR traffic reduces up to 67% comparing to that of Case 1). The average time delay of Case 2) improves 28% for CBR traffic and 32% for VBR traffic comparing to that of Case 1). With a RR scheduling scheme, the PC has to poll all stations in SCP so that the CFP can be dominated by the two polling frames from the PC and the SR frames from stations when the number of stations are large. On the other hand, by dynamically changing the number of stations in the polling sequence of SCMP based on the expected

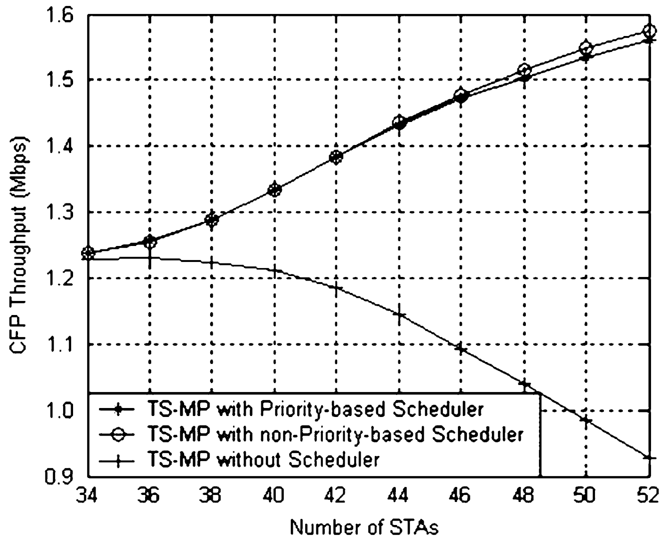


Fig. 11. Comparison of CFP throughputs for the three configurations.

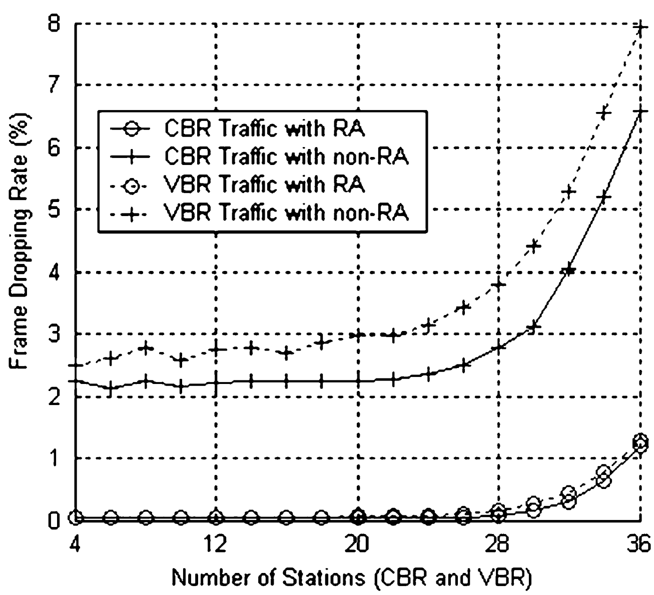


Fig. 12. Comparison of dropping probabilities between TS-MP with rate adaptation and without rate adaptation.

buffer status for each station, the proposed scheduling scheme not only prevents the CFP from being dominated by the two polling frames and the SR frames, but also increases the time portion for data transmission. These results are reflected in the CFP throughput as shown in Fig. 11. Using the proposed scheduling scheme, performance improvement is achieved through removing unnecessary overhead.

Now, we compare the performance of Case 3), under which stations in the BSS are scheduled with different priorities depending on the traffic type. The dropping probability and the average frame delay of the CBR traffic in Case 3) decreases up to 46% and 21% compared with corresponding values in Case 2). For the VBR traffic, the dropping probability and the average frame delay in Case 3) are up to 7% and 20% higher than the corresponding values in Case 2). These results reflect the fact that the CBR traffic is given higher priority by the scheduler.

E. Rate-Adaptation (RA) Functionality

Now, we show the adaptability of our protocol over the time-varying channel. The protocols are evaluated under the Ricean fading channel with Ricean parameter K set to 5. Thus, all communication links experience different channel condition on every superframe. Fig. 12 shows the frame dropping probabilities of TSMP with RA and one without RA. Using the rate adaptation function of TSMP, we can reduce the dropping probability by 70% up to 98% comparing to that of TSMP without RA. This shows the adaptability of our polling scheme against the time-varying wireless channel.

V. Conclusion

In this paper, we propose a new polling-based MAC protocol for the PCF in IEEE 802.11 WLAN. The major innovation is the use of two MP frames with different purposes. Through the first MP, the PC obtains information required to schedule the polling sequence for data transmission. The second MP coordinates data transmissions without collision. Comparing with the single polling scheme used in the conventional IEEE802.11 MAC protocol, the proposed scheme can reduce the overhead caused by the polling frames. For most previously proposed protocols in the literatures, the PC does not have information about the appropriate physical transmission rate for communication link and the buffer status of each station involved in the PCF. As a consequence, simple scheduling schemes, such as the RR scheduling scheme, is used. However, the proposed protocol makes it possible for the PC to schedule the polling sequence based on the currently obtained information from all stations. Therefore, by utilizing the information, we can design more efficient scheduling schemes. From the extensive performance simulation, we have shown that the proposed polling-based MAC protocol gives significant performance improvements over the other polling-based MAC protocols.

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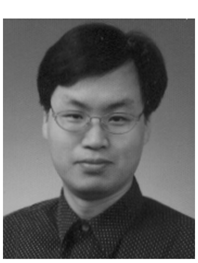

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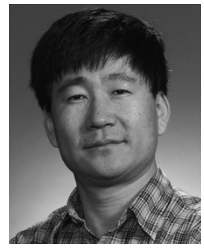

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