A New Cross-layer Designed Multipolling MAC Protocol over WLANs

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Abstract— **In this paper, we develop a multipolling MAC protocol which exploits cross-layer information to support delay-senstive multimedia services over WLANs. A user detection module and a multi-rate adaptation module are proposed in the physical layer to assist in link differentiation. With these two modules, our new multi-polling MAC protocol, named PALD-MPMP not only reduces the polling overhead, but also provides an effective polling scheduler by allocating transmission priorities to users according to their delay requirements or levels and channel gains. Simulation results show that our proposed protocol outperforms the standard point coordination function (PCF) for delay-sensitive services. All the performance improvements are mainly contributed by the awareness of cross-layer channel state information, and the consequent multi-rate adaptation schemes.**

I. INTRODUCTION

IEEE 802.11 WLAN [1] has emerged as a prevailing technology for (indoor) broadband wireless access. The standard MAC protocol consists of two coordination functions: contention-based distributed coordination function (DCF) and contention-free point coordination function (PCF). The DCF scheme is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. In PCF, the channel access of each station is controlled by polling from a point coordinator (PC) at the access point (AP). DCF is originally designed to support best-effort data services, while PCF is targeted to support delay-sensitive multimedia services, such as voice and video applications. DCF and PCF can coexist by alternating between a contention free period (CFP) ruled by PCF and a contention period (CP) ruled by DCF.

With the increase of capacity of WLANs, real-time multimedia applications which need quality-of-service (QoS) guarantees have become popular. Since the controlled channel access scheme can reduce the time wasted for accessing the channel during the backoff process in DCF, PCF is an appropriate scheme for users with QoS requirements. However, the IEEE 802.11 MAC specifies a round-robin (RR) polling mechanism whereby the AP polls the stations in ascending order of their association IDs (AIDs). This algorithm is easy to implement. However when the number of stations in the polling list increases, stations will suffer from long access delays. Bandwidth wastage is caused due to sending CF-Polls and Null packets for the stations which have no pending packets. In addition, PCF only defines a single-class scheduling algorithm, which cannot handle the various types of traffics with different QoS requirements. For efficient polling, several types of multipolling protocols were proposed in [3], [4] and [5]. All of them introduce a rather long status collection period at the beginning of CFP, which increases the complexity and overhead.

For DCF, [2] proposed a method to distinguish between collisions and link errors in the MAC layer. For a frame loss, if the sender receives a CTS but no ACK, it deduces the loss is caused by wireless errors; if the sender receives neither a CTS nor an ACK, it deduces the loss is caused by collisions. In our paper, for contention-free medium access control, an effective user detection module and a multi-rate adaption module in the physical layer are designed to feed back active users' ID, detected channel conditions, and maximum supported data rate information to APs to help them increase the polling efficiency and the bandwidth utilization. Based on these two modules, a new cross-layer designed multipolling MAC protocol, named PALD-MPMP, is proposed, which is characterized by: 1) an effective polling list is managed with the priority based on delay requirements or levels; 2) the polling sequence is sorted by the channels' detected state information and multi-rate adaptation information; 3) the multipolling scheme decreases the polling overhead and increases the bandwidth usage.

The rest of this paper is organized as follows. Section II presents the physical layer user detection and multi-rate adaptation modules. The detailed description of PALD-MPMP is introduced in Section III. Sections IV shows the simulation results. Section V concludes this paper.

II. USER DETECTION AND MULTI-RATE ADAPTATION MODULES

A. User Detection Module

In IEEE 802.11, there are two types of WLAN topologies: the independent basic service set (IBSS) as an ad hoc network, and an infrastructure network, as shown in Fig. 1. In an infrastructure network, an access point (AP) acts as a hub and connects the basic service set (BSS) network to

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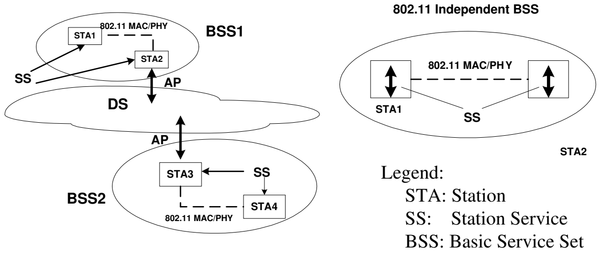


(a) Infrastructure network (b) Ad hoc network

Fig. 1. WLAN network topologies.

the distributed system (DS). According to the statement of logical service interfaces in [1], the necessary information is exchanged between the AP and other nodes by association-related services and authentication-related services at network initialization. Among such information, we are most interested in the transmitter addresses (TAs) of the active nodes and such information is readily gathered by the APs.

Multiuser detection is an effective technique in CDMA systems. It can successfully separate users at the receiver based on their unique spreading codes [6]. In WLANs, there exists similar user dependent information - transmitter address (TA), which is included in RTS frames. Assuming users can synchronously or asynchronously send RTS frames, some multiuser detection methods can be adapted to WLAN systems, and provide further channel condition information. Based on this information, it is ensured that the MAC protocol can schedule the different users' transmissions, accounting for the users' QoS requirements. In terms of the throughput, by eliminating unnecessary polling overhead and scheduling polling sequence with channel information, user detection can effectively improve the network performance. In this section, a synchronous user detection method for WLANs will be presented. If RTSs can not be transmitted synchronously, some asynchronous multiuser detection techniques used in CDMA systems can be used to support the physical layer link differentiation.

Consider a BSS system where K mobile nodes are associated with an AP. After the network initialization, the AP keeps a transmission address list of the active users in its BSS. The transmitter address of mobile node k is $\mathbf{c}_k$, an N-bit ($N = 48$) vector, so the list of TAs can be recorded as follows:

$$\mathbf{C} = \left[\begin{array}{ccccc} \mathbf{c}_1, & \cdots, & \mathbf{c}_k, & \cdots, & \mathbf{c}_K \end{array}\right],$$

where $\mathbf{c}_k = \left[\begin{array}{ccccc} c_{k,1}, & \cdots, & c_{k,n}, & \cdots, & c_{k,N} \end{array}\right]^T$ and $c_{k,i}$ is the ith bit of the N-bit address $\mathbf{c}_k$. As in a synchronous CDMA system, if TAs are orthogonal to each other, then the best detection performance will be achieved. Therefore, in WLAN systems, to improve the detection performance, orthogonal 48-bit vectors can be re-assigned to users as TAs in BSSs. Each orthogonal vector corresponds to each TA in a BSS and for different BSSs, these orthogonal vectors can be reused. For K users, the vector $\mathbf{h}$ represents the channel gains experienced in their respective wireless channels:

$$\mathbf{h} = \left[\begin{array}{cccccc} h_1, & \cdots & , & h_k, & \cdots, & h_K \end{array}\right]^T.$$

At time t, we assume that l ($0 \leq l \leq K$) users have data to transmit and send RTSs simultaneously to contend the channel. For users who have not sent RTSs, their corresponding channel gains in vector $\mathbf{h}$ will be zero. After the RTS contention procedure, the received signal is given by

$$\mathbf{r} = \mathbf{C}\mathbf{h} + \mathbf{n}, \tag{1}$$

where $\mathbf{n}$ is the noise. Consequently, according to the least-squares criterion, the users' channel gain vector is estimated at the receiver by the following formula:

$$\hat{\mathbf{h}} = (\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T\mathbf{r} = \mathbf{\Pi}\mathbf{r}, \tag{2}$$

where $\mathbf{\Pi} = (\mathbf{C}^T\mathbf{C})^{-1}\mathbf{C}^T$. Basically, each calculated element $\hat{h}_k$ represents the detected channel gain of each active user. It is necessary to distinguish three cases:

1) Silence state: the active node has no RTS requirement in the current contention round.

2) Link error state: the active user takes part in the channel contention; however, its channel quality is deduced to be inadequate for transmission.

3) Collision state: the active user attends the contention and obtains a good channel to transmit its pending frame.

In order to implement the above differentiation function, our user detection module utilizes the power value of h_k, namely $|\hat{h}_k|^2$, as the decision criterion, and then constructs two thresholds to discriminate the above three cases. For those users who have not participated in the RTS contention, their $|\hat{h}_k|^2$ values should be zero. However, with noise present, the value of $|\hat{h}_k|^2$ could be nonzero. So, it is required to set a few thresholds for different users to distinguish the first case from the other two cases. By substituting (1) in (2) , we obtain:

$$\hat{\mathbf{h}} = \mathbf{h} + \mathbf{\Pi}\mathbf{n}. \tag{3}$$

Clearly, the power of the noise signal in the vector $\mathbf{\Pi}\mathbf{n}$ should be the lower bound of the silence threshold. We assume $\mathbf{n}$ is an additive white Gaussian noise vector whose elements have zero mean and variance σ^2. Denote the calculated inverse matrix by $\mathbf{\Pi} = [a_{i,j}]_{K\times N}$, then we obtain the silence threshold:

$$\begin{aligned} H_{silence-thresh} &\geq E\{|\mathbf{\Pi}\mathbf{n}|^2\} \\ &= \sigma^2 \times \Big[\textstyle\sum_{j=1}^{N}(a_{1,j})^2, \cdots, \\ &\quad \textstyle\sum_{j=1}^{N}(a_{k,j})^2, \cdots, \sum_{j=1}^{N}(a_{K,j})^2\Big]^T_{1\times K}, \end{aligned}$$

where $|\cdot|$ is an operator to take the absolute value of each element in a vector. We denote the second threshold as $H_{collision-thresh}$ to distinguish the second case from the third case. This parameter is related to the specific system performance, the user's QoS requirements, etc. In practice, the value of $H_{silence-thresh}$ will be chosen between the above lower bound and $H_{collision-thresh}$. For a particular network scenario, we can obtain an effective value which can minimize the error detection through simulations.

It should be mentioned that since $N = 48$, the maximum number of detectable users is 48. If there are more than 48 active users, we can consider adding additional address information in the RTS frame or assign longer orthogonal addresses for them, but this will cause additional overhead. Alternatively, we can distribute additional users to other APs.

B. Multi-rate Adaptation (MRA) Module

By using the concept of adaptive modulation [7], stations in a multi-rate WLAN system are assigned the modulation scheme and transmission rate according to the detected signal-to-noise ratio (SNR) and the required transmission quality. Each modulation scheme could be further mapped to a range of SNR at a given transmission power. To achieve high transmission efficiency in WLANs, stations shall select the highest available rate modulation scheme according to the detected SNR. Based on the above user detection module, we assume that the noise power is detected at silent periods before the start of data transmissions, so APs can easily estimate the noise power by $\hat{\sigma}^2 = \parallel \hat{\mathbf{n}} \parallel^2 /N$. Furthermore, by the definition of SNR, for any active user, we can easily detect its SNR value:

$$\hat{SNR}_k = \frac{|\hat{h}_k|^2}{\hat{\sigma}^2} \ (k = 1,\ 2,\ \cdots,\ K).$$

In this paper, we are mainly concerned with the 802.11b WLAN which provides 4 types of supported rates. Without MRA, we assume the channel state is either good or bad, differentiated by the $H_{collision-thresh}$. With MRA, a set of SNR thresholds should be defined in order to select the appropriate data rates in the physical layer (PHY). In the simulations, these thresholds have been selected based on the results presented in [8].

$$R = \begin{cases} 1\ Mbps & (BPSK), & SNR < \gamma_1 \\ 2\ Mbps & (QPSK), & \gamma_1 \leq SNR < \gamma_2 \\ 5.5\ Mbps & (CCK), & \gamma_2 \leq SNR < \gamma_3 \\ 11\ Mbps & (CCK), & \gamma_3 \leq SNR \end{cases}$$

III. PALD-MPMP DESCRIPTION

A. Protocol Description

Based on the above physical layer assisted link differentiation scheme, the proposed MAC protocol should address two points: 1) how to synchronize the required RTSs? 2) if the co-existing synchronized RTS signals are separated, and the channel state information is detected, how to make use of such information to schedule the data transmissions effectively? The following will give the answers.

Fig. 2 shows the timing diagram of PALD-MPMP. The CFP period consists of several sub-polling periods (SPP).

$$\sum_{i=1}^{N} SPP_i \leq CFP,$$

where N is the maximum number supported in a CFP period and its value is dynamically changed in each CFP period. Each SPP is further divided into two subperiods: station selection period (SSP) and data transmission period (DTP). To illustrate the implementation of PALD-MPMP, three issues will be discussed in this subsection: management of the polling list, determination of the polling sequence, and processing of the multipolling scheme. The first two functions are performed in SSP, while the third one is done in DTP.

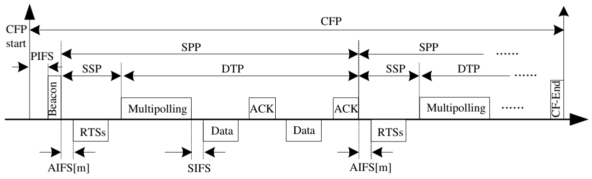


Fig. 2. Timing diagram of PALD-MPMP.

1) Management of the Polling List: As introduced in the previous section, after the synchronized RTSs from users who have transmission requirements are received at an AP, the physical layer assisted link differentiation can effectively obtain the active users' ID, channel gain, and supported maximum transmission rate information. Therefore, at the beginning of each SSP period, synchronized RTSs from the users who have pending data are transmitted to an AP, to help the user detection and multi-rate adaptation modules differentiate wireless links. When considering different classes of realtime services in contention-based medium access control, such as voice and video traffics, the enhanced distributed channel access (EDCA), which is being developed in the standard IEEE 802.11e [9], assigns different arbitration interframe space (AIFS[i], i=0, ..., 3) to distinguish the different access priorities. The AIFS[i] can be enlarged with the help of the arbitration interframe space number (AIFSN[i], i=0, ..., 3). The AIFSN[i] defines the duration of AIFS[AC] according to:

$$AIFS[i] \quad = \quad SIFS + AIFSN[i] \times aSlotTime,$$

where $AIFSN[i] \geq 1$. The parameter aSlotTime defines the duration of a slot. The smaller the AIFSN[i] the higher the medium access priority. In our contention-free medium access control, since the polling strategy is targeted at satisfying the QoS for different time-bounded services, we set the transmission priorities according to the delay levels and these delay levels are set by the delay bounds of different services. In this paper, we assume only the delay-sensitive users are pollable and simply choose voice delay bound and video delay bound to distinguish the users' different access priorities. Among the users who have pending data to send, those whose packet expiration time is shorter than the voice delay bound have a higher access priority than those users whose packet expiration time is between the voice and video bounds. To control the access of various delay level requirements, AIFS[m] (m=1, ..., M) is also adopted, where AIFS[m] has the same definition as in EDCA and M is the number of total delay levels. It is noted that these AIFSs do not contradict with PIF used at the initiation of a CFP. AIFSs are only used between the CFP beacon and CFP end period. Since only voice and video delay bounds are considered, values 0 and 1 are assigned to AIFSN[1] and AIFS[2], where $AIFSN[m] \geq 0$. In each SPP, stations which send RTSs at the same delay level will be added into the polling list.

2) Determination of the Polling Sequence: After the synchronized RTSs are received at an AP, the physical layer user detection and multi-rate adaptation modules can detect the corresponding users' channel gains and further deduce their supported maximum transmission rates. With this collected information, at the same delay level, users who have better channel gains or higher supported data rates will have higher transmission priorities.

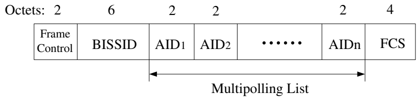
3) Multipolling Processing: After collecting the users in the same delay level into the polling list and sorting their transmission sequences by channel gains, APs use a multipolling frame to control the wireless medium in PALD-MPMP. In order to demonstrate the impact of the MRA scheme on the performance, our PALD-MPMP broadcasts two multipolling frame formats, which are different in the content of the multipolling list and supported rate field, as shown in Fig. 3.

i) Without MRA, the multipolling list only includes the AIDs of the users whose channels are in collision states. PALD-MPMP sorts the mulitpolling list by the users' deduced power values of the channel gains. It is noted that a TA is the address of a station transmitting a frame. An AID is the value assigned to a station transmitting a frame by the AP in the association response frame that established that station's current association.

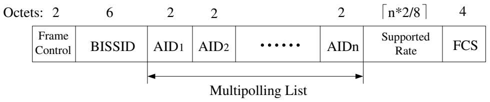
ii) Let us consider users with both collision and link error channel states. With MRA, different supported data rates can be dynamically chosen according to the users' current detected SNRs. This can eliminate the packet losses due to lower SNRs and ensure high efficiency code modulation for the users with high SNRs. Therefore, the multipolling list should not only include the AIDs of the collided users, but also the AIDs of the link error users. In addition, their supported maximum data rates shall also be reported back to the users which sent RTS frames. Since the IEEE 802.11b WLAN system supports four types of data rates, 2 bits are assigned for each user to indicate the currently supported data rate. Assuming the number of the users to be polled is n, the rate information in the multipolling frame needs $\lceil n \times 2/8 \rceil$ bytes.

After receiving this multipolling frame with MRA information, each polled user will transmit its data with supported maximum data rates after the AP has acknowledged the user preceding it in the multipolling list. In the first SPP, RTSs are easily synchronized after a period of AIFS[m]. For the subsequent SPPs, we utilize the following method. In the frame control field of MAC headers, there is a one-bit "More Fragment" field, which indicates whether there is another fragment of the current MAC service data unit (MSDU). Our protocol utilizes this bit in each ACK to inform all active users whether this ACK corresponds to the last polled user. If it is, after a period of AIFS[m], users who have RTS requirements will contend the channel again, and the synchronization of RTSs can be achieved.

Fig. 4 show the flow chart of PALD-MPMP. The following is its brief description.



(a) Without MRA support



(b) With MRA support

Fig. 3. Mulipolling frame format.

(1) In a CFP, after the beacon frame, if stations with pending data to send have a higher priority in delay level, such as the stations whose delay expiration time is less than the voice delay bound, after a period of AIFS[1], these stations will send RTSs. With the user detection and multi-rate adaptation modules, the polling list is managed and sorted according to their detailed channel conditions. Then the multipolling processing starts and continues till the last ACK with the "More Fragment" equal to 1 is broadcast by the AP. The current SPP is finished.

(2) In a new SPP, if new transmission requirements with a higher priority are generated, after another AIFS[1], (1) is repeated.

(3) If no higher priority data transmission requirement in delay level is generated, stations with lower priority, such as those stations whose delay bound is more than the voice delay bound but less than the video delay bound, could be scheduled after a period of AIFS[2], and data transmission goes on in this SPP.

(4) If after AIFS[m], no RTSs are transmitted, i.e., no stations have data to send, after RTS timeout, this CFP will end with a CF-End frame.

B. Performance Analysis

In PCF, even with a piggybacking scheme, all stations must be polled regardless of whether a station has pending frames or not because the PC does not have any knowledge about the stored frames and their delay information. Thus bandwidth wastage due to polling stations which have no pending frames is inevitable. In PALD-MPMP, only users who have pending data send RTSs before frame transmissions. To distinguish service delay priorities, these RTSs are sorted according to different delay levels. When the synchronized RTSs at the same delay level are received by an AP, the collided users with good channels can be effectively separated and their transmissions are scheduled. Suppose a transmission of an RTS experiences a weak channel. Without the MRA scheme, it will be deferred to the next SPP, without wasting any polling overhead. With MRA, the subsequent data transmission will be served with a lower data rate.

When considering the effect of noise, in PALD-MPMP, the

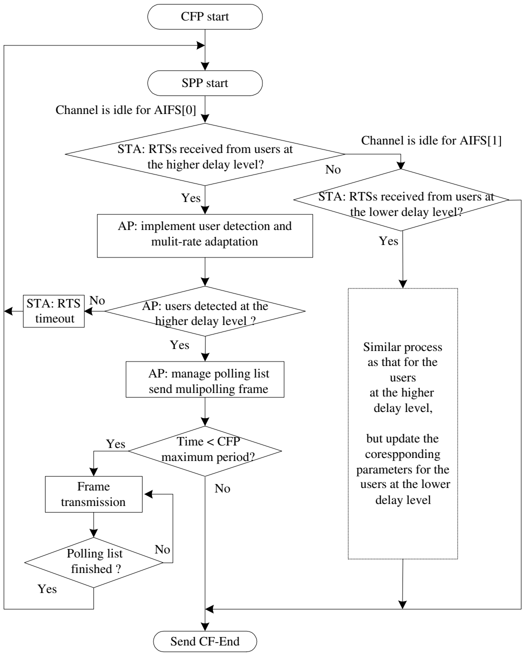


Fig. 4. Flow chart of PALD-MPMP.

TABLE I
NOTATIONS AND PARAMETER VALUES

Notations	Descriptions	Values
MAC	MAC header overhead	224 bits
DIFS	The period of PIFS	30 μs
SIFS	The period of DIFS	10 μs
RTS	RTS frame size	160 bits
ACK	ACM frame size	112 bits
PHY	PHY header overhead	192 bits
DataRate	Constant data rate without MRA	5.5 M
t_p	Propagation delay	1 μs

TABLE II
VOICE AND VIDEO TRAFFIC MODELS

Voice Model	Values	Video Model	values
Talkspurt	1 s	Peak rate	420 Kbps
Silent gap	1.35 s	Minimum rate	120 Kbps
Data rate	64 Kbps	Average rate	240 Kbps
Delay bound	25 ms	Mean state time	160 ms
Packet size	200 Byte	Delay bound	50 ms
		Packet size	800 Byte

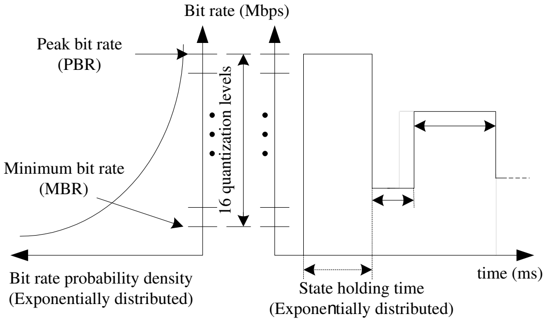


Fig. 5. Traffic model of VBR.

user detection module uses $H_{silence-thresh}$ to identify the active users who have RTS requirements. If the effect of noise is small, the deduced threshold is effective. When the noise is large, we need to consider two types of errors caused by the improper threshold. One type occurs when a user sends an RTS on a weak channel. The value of $| \hat{h_k} |^2$ should be between $H_{collision-thresh}$ and $H_{silence-thresh}$, but the detected result is lower than the corresponding $H_{silence-thresh}$. In this case a user will wait till timeout, and then attend the next SPP, without further polling overhead. The other type occurs when a user has not sent an RTS, but the detection module mistakenly includes its AID in the polling list. In this case, the user sends a null frame to the AP, but in practice, this case will rarely happen.

IV. SIMULATION RESULTS

A. Simulation Models

This subsection presents the simulation results of the standard PCF with piggybacking scheme, PALD-MPMP without MRA and PALD-MPMP with MRA. In the physical layer, a Raleigh fading model with channel power equal to 1 is chosen. Channel noise is assumed to be white Gaussian with average SNR equal to 20 dB. In addition, we use $H_{collision-thresh}$ to control the network packet loss rate (PLR) to equal 0.1. All simulations in this paper are of 100s duration. Simulation topologies are WLANs where K delay-sensitive stations are connected with an AP. Simulation parameter values are configured as in Table I. We assume that each station generates a single type of traffic. There are 12 voice and 12 video stations. The parameters of the voice and video models are summarized in Table II. The following is the description of the two traffic models:

1) Voice Traffic Model with Constant Bit Rate (CBR): The voice traffics are modelled as a two-state Markov process with talkspurt and silent-gap states. The duration of talkspurt and silent-gap both follow the exponential distribution with the mean duration equal to 1 s and 1.35 s, respectively.

2) Video Traffic Model with Variable Bit Rate (VBR): As shown in Fig. 5, the video traffics are modelled as a multiple-state model where a state generates a continuous bit stream for a certain holding duration [10]. The bit rate values of different states are obtained from a truncated exponential distribution with minimum and maximum bit rate values. The holding times of the states are assumed to be statistically independent and exponential distributed.We assume that each state has the same mean holding time. In the simulations, the generated VBRs are quantized into 16 levels.

B. Numerical Results

1) Throughput comparisons: Fig. 6 shows the average throughput comparisons of the different services. For both

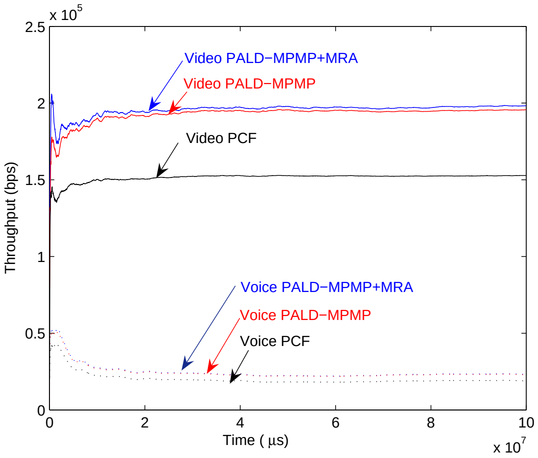


Fig. 6. Throughput comparisons.

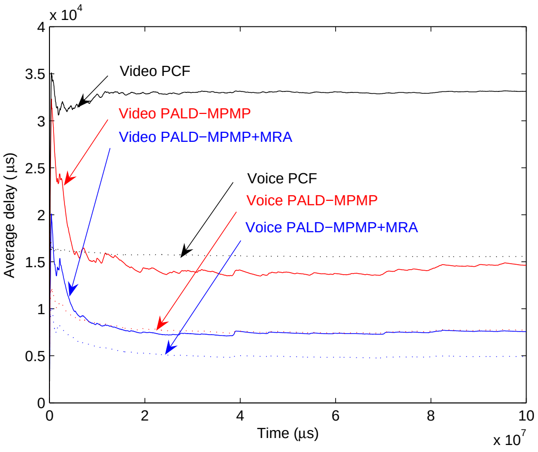


Fig. 7. Delay comparisons.

CBR (voice) and VBR (video) traffics, our proposed PALD-MPMP protocol has obvious throughput improvements. With MRA, further improvements are obtained.

2) Delay comparisons: In Fig. 7, it is obvious that for both CBR and VBR transmissions, the delays are lower in PALD-MPMP. For PALD-MPMP with MRA, better delay performances are obtained by reducing the frame transmission time with higher supported data rates.

3) Dropping rate comparisons: In Fig. 8, for both voice and video traffics, the dropping rates are around 0.2 in PCF. In PALD-MPMP without MRA, the values drop to 0.01. With MRA, the dropping rates are nearly zero.

V. CONCLUSIONS

Based on the physical layer assisted link differentiation mechanism, to support QoS for multimedia transmissions, a cross-layer designed multipolling MAC protocol, named PALD-MPMP, is proposed. With the synchronization of RTS frames and the awareness of TAs in the MAC layer, the user detection and mulit-rate adaptive modules in the physical layer can detect active users' IDs, channel gain, and maximum data rate information. Using such information, PALD-MPMP provides an effective multipolling scheme for services with different delay levels. It decreases the polling overhead and gives QoS guarantees for delay-sensitive services. Simulation results show that PALD-MPMP can improve the throughput performance and decrease the delays and dropping rates for both VBR and CBR traffics.

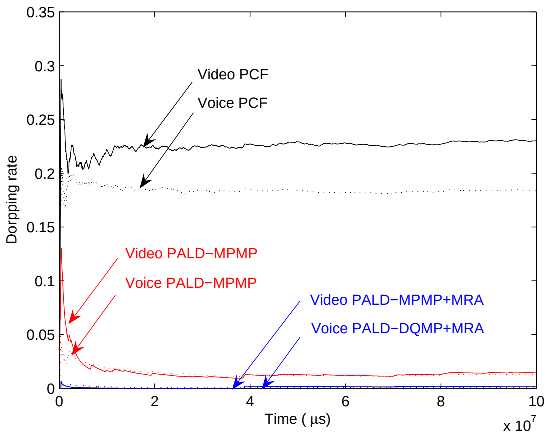


Fig. 8. Dropping rate comparisons.

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