PRMA/DA: A New Media Access Control Protocol for Wireless ATM

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Abstract

In this paper, we propose a media access control (MAC) protocol for wireless local area networks (LANs) that is capable of supporting various types of traffic demands, such as constant bit-rate (CBR) voice, variable bit-rate (VBR) video, and packet data. In addition, the proposed protocol provides a seamless connectivity to a broadband ATM backbone network. Our protocol, having an air interface comparable to ATM, adopts a dynamic channel allocation scheme which enables expeditious network access and utilizes bandwidth resource efficiently. The simulation results presented in this paper shows the improvements of dynamic channel allocation over the static channel allocation scheme in terms of key performance metrics such as: throughput, call blocking probability, network access delay, and cell transmission delay.

1 Introduction

With the rapid proliferation of high performance portable computers and mobile devices such as personal digital assistants (PDAs), the demand to connect all these devices to the fixed network (such as Asynchronous Transfer Mode) in a seamless fashion has been rapidly increasing. In particular, wireless local area networks (LANs) are expected to be a crucial enabling technology in traditional office settings [1], [5]. A major technical issue related to wireless LANs is concerned with the selection of a suitable media access control (MAC) protocol to efficiently arbitrate multiple mobile stations (MSs) on a common shared medium [5]. Several MAC protocols have been proposed for the wireless LANs. The protocols include Packet Reservation Multiple Access (PRMA), Code Division Multiple Access (CDMA), variants of PRMA, etc.

PRMA is a statistical multiplexing method for delivering speech signals via a TDMA system [2], [7], [8]. Although PRMA is initially designed to carry voice traffic only, current efforts in computer networking for both wired and wireless segments are directed at supporting multimedia traffic [1]. Thus, future wireless personal devices are expected to support multimedia applications such as image retrieval, video conferencing as well as traditional voice and data. To cope with the necessity of transporting other media plus voice, the enhanced version of PRMA called IPRMA (Integrated PRMA) is proposed to transmit both speech and data packets with higher throughput [4]. The novelty of the proposal comes from the fact that data users may reserve multiple slots across a frame to increase system throughput. While IPRMA is not intended to support multimedia traffic, the work by Raychaudhuri *et al.* [1] introduces the multimedia capable integrated services wireless networks in an ATM-based transport architecture. In this study, multiservice-dynamic-reservation time-division-multiple-access (MDR TDMA) is employed as a MAC method. In the MDR TDMA, a TDMA frame consists of request slots and message slots. The request slot is relatively small and is used for random access to the system based on the slotted ALOHA. The message slot is used to carry CBR (Constant Bit Rate), VBR (Variable Bit Rate), or ABR (Available Bit Rate) traffic once reservation is granted. Rather than using the fixed frame scheme, another enhanced variation of PRMA, called C-PRMA (Centralized PRMA), adopts a hybrid random access and polling scheme [3]. Random access techniques are used by the mobile stations to reserve slots for a message transmission, while the information packets are transmitted by using a polling scheme managed by the BS. The main features of C-PRMA are the capability to integrate several classes of service and provide a prompt retransmission method for corrupted packets.

In this paper, we propose an efficient MAC protocol for wireless ATM, which is suitable for multimedia applications requiring a wide range of telecommunication services such as CBR, VBR, packet data (ABR), and others. Each application category has its own service requirements. Thus we need a MAC protocol that can meet the different requirements simultaneously in order to enable integrated transmission in a wireless ATM environment. Our proposal is based on the PRMA protocol and does not require mini (request) slots which incur a certain fixed overhead. In particular, our proposed method increases the role of the BS to also act as a *bandwidth allocation manager*. A mobile station can get admitted to the network or is allowed to increase its transmission rate only when it gets permission from the BS. Mobile stations becoming active try to access the network by grabbing the available (unused) slot in a frame. The simultaneous access to the slot among the multiple stations leads to collision. To relieve the network access delay, we introduce the concept of *dynamic allocation of available slots* which may allow contending stations to have freer access to the available slots. The available slots can expand or shrink depending on the congestion state of the network. In addition, our protocol can flexibly allocate slots based on the traffic parameters specified by the users during the connection set-up phase, such as the average number of cells generated during a frame period. The traffic parameters have an important role in deciding call admission.

The structure of the paper is as follows. In Section 2, we propose a modified version of PRMA to handle multiservice wireless applications. In Section 3, we describe the simulation model with pertinent numerical parameters. The simulation results are discussed in terms of the important performance measures such as throughput, call blocking probability, network access delay, and cell transmission delay. We conclude the paper in Section 4.

2 The Protocol

2.1 Basic Operation

The proposed MAC protocol, called PRMA/DA (Packet Reservation Multiple Access/Dynamic Allocation), is designed to operate in the conventional cellular system architecture. In the cellular architecture, a base station (BS) is located in the center of a cell with mobile stations (MSs) dispersed inside the cell. All the communication services present in the cellular architecture are made by having the BS relay the traffic between the communication participants. Depending on the direction of transmission between the MS and the BS, the communication channel in PRMA/DA is categorized into two separate time-slotted channels: *uplink* channel and *downlink* channel. The uplink channel delivers the information from the MSs to the BS, while the downlink

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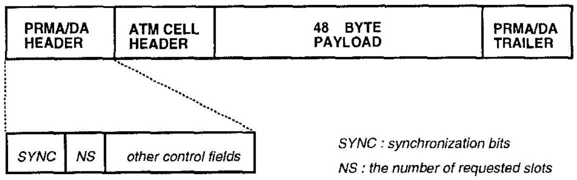

Figure 1: Cell format at the air interface.

channel is used to communicate in the opposite direction. For the uplink transmission, the mobile stations in a cell share the communication channel using the PRMA/DA protocol. The downlink channel operates with a contention-free TDM (time-division multiplexing) broadcast mode.

PRMA/DA adopts a packet switching scheme comparable to the ATM transport architecture. Next generation wireless local networks will be required to co-exist with ATM network, which should be deployed in the near future [1]. Based on the considerations, we adopts the ATM cell relay paradigm as the basic transport architecture. Thus an ATM cell acts as a fundamental unit of protocol processing and switching in both wired and wireless network segments. The typical structure of the transport cell at the air interface is illustrated in Fig. 1. As shown in the figure, the ATM cell is encapsulated by a PRMA/DA header and trailer. The header contains synchronization bits, a *NS* field indicating the number of slots requested from a mobile station, and other control fields, while the trailer minimally contains an error check field. The *NS* field is of importance to the operation of the protocol, since the field is used to carry the information on the current bandwidth demand of a mobile station to the BS at every frame.

PRMA/DA operates on the frame basis. Time on the uplink channel is divided into a contiguous sequence of PRMA/DA frames, which are further subdivided into a fixed number of slots. In particular, a PRMA/DA frame can be segmented into *available* slots and *reservation* slots consisting of CBR reservation slots, VBR reservation slots, and ABR reservation slots as illustrated in Fig. 2. The BS has absolute control in determining the number of both available slots and reservation slots. Furthermore, the BS also specifies the number of slots assigned to each individual reserving station. The number of available slots depends on the intensity of demand to access the network among the mobile stations. In contrast, the number of reservation slots assigned to each reserving station is primarily dependent on the statistical properties of traffic a MS intends to transmit.

Each group of slots in a frame provides specific service characteristics. The available slots provide a communication mechanism for a mobile station to attain network access, while the reservation slots supply a mobile station with a major resource of channel bandwidth during a network access (or connection) period. In order to transport the traffic, an activated station needs to access the network. The network access is made by transmitting a cell in a randomly selected available slot. After completing the contention procedure, the mobile station can use the reservation slots without undergoing further contentions.

The contention procedure of the PRMA/DA protocol operates on a random access (slotted ALOHA) scheme. A mobile station, when it has just become active, switches its mode into the *contention* mode from the *inactive* mode. A mobile station in the contention mode is called a *contending* station in PRMA/DA terms. As in the slotted ALOHA, a contending station randomly selects one of the available slots which occupy the beginning portion of a frame. The available slots are numbered from 1 to N_a as shown in Fig. 2. A contending station randomly chooses a number ranging from 1 to the number of available slots (N_a) and transmits the cell in the selected slot. As an example, the mobile

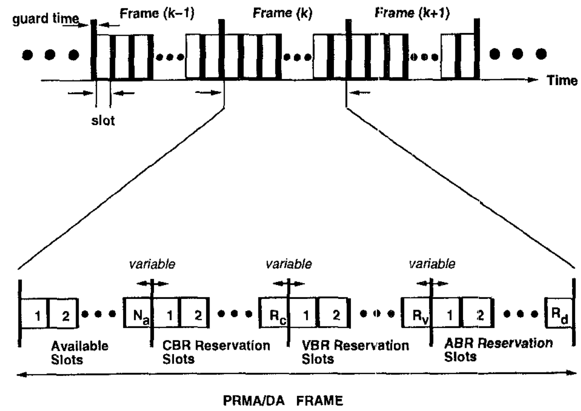

Figure 2: The PRMA/DA frame format

station that chooses the random number k ($1 \leq k \leq N_a$), must transmit its first cell in the k th available slot. Right after the contention period, the BS advises the contending stations whether the network access is successful or not.

Unless other contending stations try to transmit their cells in the same slot, the mobile station will attain the network access and shift its mode to the *reservation* mode. If the mobile station fails to acquire the network access due to a collision, it needs to repeat the contention procedure at the next frame. The BS broadcasts the new N_a value at the end of each frame. Upon receiving the information, the contending stations prepare for the next contention period. For CBR/VBR traffic, which has stringent timing constraints, the unbounded repetition of the contention procedure is meaningless. Therefore, we specify the maximum time for contention which is called *maximum setup time* (W_{max}). If a contention period of a mobile station lasts longer than the maximum setup time, its call will be discarded and the mobile station will return to the inactive mode.

The number of the available slots in PRMA/DA varies dynamically depending on the congestion state of the network. The objective of the scheme is to maximize the throughput by having the majority of slots serve the reserving stations while maintaining a minimal number of available slots for contending mobile stations. As the demand for network access increases, the number of available slots will expand according to the algorithm which will be discussed later in detail. With decreasing requests for network access, the number of available slots will shrink accordingly. Finally the number of available slots reduces to one when no demand exists.

The number of reservation slots assigned to the reserving stations is governed by the dynamic allocation algorithm. The primary factor considered in the algorithm is the statistical properties of the traffic that a mobile station intends to transport. At the connection setup phase, a contending station is required to specify the traffic parameters in the cell that is delegated to contend for an available slot. In the current phase of our work, the statistical properties of the traffic are represented only in terms of the average number (R_m) and peak number (R_p) of cells generated during a frame period. Further extension will be required to more accurately characterize the traffic. Along with the parameter (R_m), the current bandwidth demand which is delivered by the NS field is considered in determining the number of reservation slots assigned to a reserving station. At the end of each frame, the BS broadcasts the information about the number of reservation slots which have been assigned to each reserving station and the respective slot locations. Upon receiving the information, the reserving stations can begin transmission in their assigned slots in a frame.

2.2 Dynamic Allocation of Reservation Slots

In a mixed traffic environment, each category of traffic, e.g., CBR, VBR, and ABR, has its own unique traffic properties and service requirements to maintain the declared QoS (Quality of Service). For instance, CBR and VBR streams have a stringent timing constraint. Furthermore, the bandwidth demand of VBR and ABR traffic fluctuates due to their bursty nature, while CBR traffic claims constant quantity of bandwidth. To cope with the heterogeneous and varying requirements, dynamic channel allocation is chosen rather than a static channel allocation which might cause inefficiency. In order to enable the dynamic allocation scheme to operate efficiently, the BS requires the following parameters: the average traffic rate (R_m), the peak rate (R_p), and the number of slots requested by a reserving station which is carried in the *NS* field of a cell. These parameters are the major factors considered by the BS when determining the number of slots to assign to a reserving station.

Once the BS determines the number of available slots (N_a), the rest of the slots in a frame are used to serve the reserving stations as shown in equation (1).

$$N_r = N_f - N_a \tag{1}$$

where N_f is the total number of slots in a frame and N_r is the total number of reservation slots in a frame.

The total number of reservation slots (N_r) is distributed to each class of traffic based on the priority of the traffic. In PRMA/DA, three categories of traffic, i.e., CBR/VBR/ABR, are prioritized in terms of their respective timing constraints. Thus the CBR/VBR reserving station has a priority in service over the ABR station. First, every CBR reserving station, i, takes $R_{p,i}$ slots since it has constant bandwidth demand which is equivalent to its traffic parameter $R_{p,i}$. The total number of slots assigned to all CBR reserving stations, $N_{r,CBR}$ is

$$N_{r,CBR} = \sum_{i \in S_C} R_{p,i} \tag{2}$$

where S_C is the set of CBR reserving stations. Second, the total number of slots assigned to VBR traffic must be at least $\sum_{j \in S_V} R_{m,j}$, where S_V is the set of VBR reserving stations. The leftover $(N_r - N_{r,CBR} - \sum_{j \in S_V} R_{m,j})$ is assigned to the ABR stations. If the ABR stations do not consume all of the available slots, the remainder is reallocated to the VBR reserving stations. It is worthwhile to transfer unused slots to a station with higher bandwidth demand. This idea is reflected in equation (3):

$$\begin{aligned} N_{r,ABR} &= \min(N_r - N_{r,CBR} \\ &\quad - \min(D_V, \textstyle\sum_{i \in S_V} R_{m,i}), D_D) \\ N_{r,VBR} &= \min(D_V, N_r - N_{r,CBR} - N_{r,ABR}) \end{aligned} \tag{3}$$

where $N_{r,VBR}$ and $N_{r,ABR}$ is the total number of VBR and ABR reservation slots respectively, and D_V and D_D is total number of slots requested by the reserving VBR and ABR stations respectively.

Slots can now be allocated to individual reserving stations. The policy for the slot allocation to an individual reserving station is very similar in principle to the case of the slot allocation to each group. That is, the reservation slots of each group are distributed in proportion to the average traffic rate (the parameter R_m) of an individual station. As in the case of slot allocation for each traffic group, the surplus slots gathered from the stations which request less will be distributed to the stations which request more, again based on their average traffic rate (R_m).

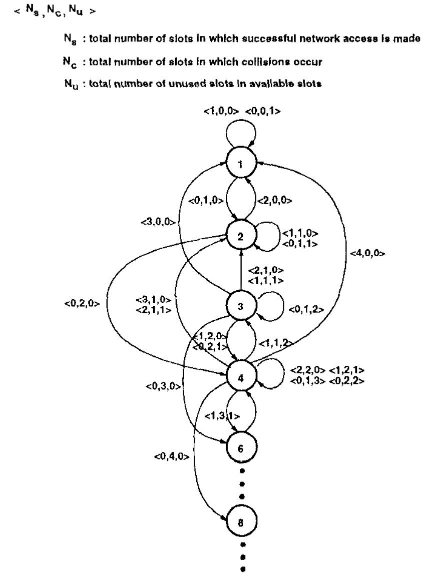

Figure 3: The state transition diagram for the number of available slots

2.3 Dynamic Allocation of Available Slots

The objective of dynamic allocation of available slots is to provide the maximum achievable bandwidth to the reserving stations and to minimize the network access delay of contending stations. In the PRMA/DA, the BS maintains only a single available slot when no demand for network access exists. However as the traffic load increases, the single slot is not sufficient to handle the network access demand of multiple contending stations. Therefore, the number of available slots needs to adapt to the intensity of the network access demand.

In the PRMA/DA, the number of available slots (N_a) is adjusted such that it approximately corresponds to the number of contending stations. The BS cannot know the exact number of contending stations present in a cell, although it can estimate the number of contending stations which were involved in collisions in the previous frame. The BS can estimate the least number of contending stations by observing the result of network access at the previous frame.

As an example, suppose that there exists a single available slot with no access demand. Also suppose that, at a certain frame, a collision occurs at the slot. Since the BS can only infer that at least two contending stations are involved in the collision, it expands the available slots to two. At the next frame, if collisions occur at the two available slots, it can be estimated in the same way that at least four contending stations are present. The BS then increases the available slots to four. At the following frame, if there exist two successful accesses, one collision and one unused slot out of four available slots, the BS decreases the available slots to two since at least two contending stations still request the network access. As explained in this example, the BS keeps track of the minimum number of contending stations. The number of contending stations can be estimated from the number of available slots (N_a), the number of successful access slots (N_s), the number of collision slots (N_c), and the number of unused slots (N_u) at the previous frame, where $N_a = N_c + N_s + N_u$. The procedure to determine N_a is described by the state transition diagram in Fig. 3. As shown in Fig. 3, the state is represented by N_a and the state change is triggered by $\langle N_s, N_c, N_u \rangle$.

The dynamic allocation for the available slots can be formalized as follows:

$$N_a^{(k+1)} = \begin{cases} \min(\max(N_a^{(k)} - N_s^{(k)}, 2N_c^{(k)}), \\ N_f - \sum_{i \in S_C} R_{p,i} - \sum_{j \in S_V} R_{m,j}) \\ \qquad \text{for } N_a^{(k)} \neq N_s^{(k)} \\ 1 \qquad \text{for } N_a^{(k)} = N_s^{(k)} \end{cases} \quad (4)$$

where $N_a^{(k)}$ is the number of available slots at the (k) th frame, $N_c^{(k)}$ is the number of slots in which collision occurs, and $N_s^{(k)}$ is the number of slots in which successful network access is made.

In the PRMA/DA, CBR/VBR reserving station i is assured to receive at least $R_{m,i}$ slots which corresponds to minimum bandwidth for maintaining the declared QoS. Therefore, in order to guarantee the minimum bandwidth for the QoS, the BS exercises the connection admission control (CAC) to prevent the admission of a new call from degrading the QoS of the reserving stations. Along with CAC, the number of available slots is bounded by a certain maximum $(N_f - \sum_{i \in S_C} R_{p,i} - \sum_{j \in S_V} R_{m,j})$ as shown in equation (4) to protect the CBR/VBR reserving stations.

3 Simulation and Performance

In this section, we provide numerical performance results for the PRMA/DA protocol operating in a mixed voice/video/data environment and compare it with its counterpart called PRMA/FA (Fixed Allocation). PRMA/FA has the exactly same principle of operation as PRMA/DA except that it does not exercise dynamic allocation of the available slots. That is, rather than delegating the BS to control the number of available slots according to the intensity of network access demand as in the PRMA/DA, PRMA/FA provides the available slots, if available, after assigning slots to the reserving stations. Therefore, the network access is dependent merely on bandwidth demands of the reserving stations. In the case where the bandwidth demand of all reserving stations exceeds the total channel capacity, a contending station will be forced to wait until an available slot is released by the reserving stations.

We use discrete event simulation to characterize the performance of the PRMA/DA protocol in a multiservice environment. The communication channel is partitioned into frames and each frame contains a fixed number of slots ($N_f = 100$). The simulation is based on a channel speed of approximately 7.067 Mb/s which corresponds to the capability of transporting, per one frame period (T), one hundred voice ATM cells digitized by a 64 Kb/s codec. In the current phase of work, we do not include the use of the VAD (voice activity detector). Thus the CBR stream (64 Kb/s) is generated during the voice call duration.

The users accessing the uplink channel in each cell are classified into three sets of users: CBR, VBR, and ABR users. A new voice call arrives at the rate of λ_v and the call duration (T_c) is exponentially distributed with an average of 3 minutes. We fix the number of VBR traffic sources to five which arrive at the beginning of the simulation. The duration of the VBR connection covers the entire simulation. A ABR call arrives at the rate of λ_d and the length of the packet is exponentially distributed with average L (5.12 Kbytes) which corresponds to about 107 cells. In order to model a VBR video traffic source, we use the video codec model proposed by Heyman *et al.* [6]. In the model, the number of video cells per frame is determined by a gamma distribution (or equivalently negative binomial) and a DAR (1) model [6].

It is assumed that a mobile station has infinite buffer capacity. Also an ideal communication channel is assumed, implying that transmission errors and retransmissions do not occur in the simulation. The simulation parameters are summarized in Table 1.

3.1 Numerical Results

The numerical results are presented here to evaluate the suitability of the proposed MAC protocol in the multiservice environment. In the experiments, the performance of two channel allocation schemes–*dynamic* and *fixed*, is evaluated in terms of key measures. The measures considered here include throughput, transmission delay, network access delay, and call blocking. The simulation model was exercised over a wide range of CBR traffic loading ($0.0 \sim 0.1908$) on both a PRMA/DA (dynamic) and a PRMA/FA (fixed) channel. All the curves in the following are plotted with 95% confidence interval.

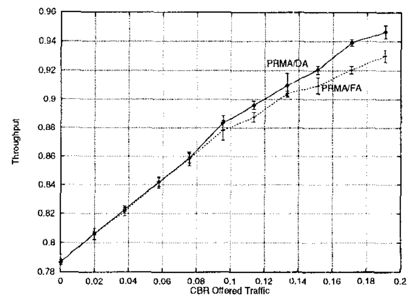

Figure 4: Throughput versus voice call offered traffic

Figure 4 shows the curves of throughput versus CBR offered traffic for the two compared cases, given that the ABR call arrival rate $\lambda_d = 0.05$ (calls/sec). As expected, the throughput curves are initially quite linear, and eventually saturate at the high load. At light offered traffic, the two schemes do not exhibit any apparent difference in throughput. However, as the CBR offered traffic increases, the curves start to show wider gaps in throughput. The result on throughput is closely related to the difference in CBR call handling between the two compared schemes.

As discussed earlier, the PRMA/DA reserves at least a single available slot for a new network user and the number of available slots is adjusted depending on the intensity of the network access demand. In contrast, PRMA/FA does not control the available slots. All the slots are used by the reserving stations as long as their bandwidth demand exceeds the channel capacity (total number of slots N_f). Thus, available slots are created only when the total number of slots requested by all reserving stations goes below the total number of slots in a frame (N_f). Thus, the outcome of an activated station attempting network access depends heavily on the current bandwidth demand of the reserving stations. However, in PRMA/DA, a contending station will get admitted to the network unless its admission degrades the performance of reserving stations, even when total number of slots requested by the reserving stations exceeds the total number of slots (N_f). The difference in the allocation scheme of the two protocols does not significantly lead to performance degradation at light load conditions ($0.0 \sim 0.07$) as seen in Fig. 4. At heavy loads, PRMA/FA is more likely to experience call blocking, thus causing lower throughput.

Curves for voice blocking probability versus CBR offered traffic are shown in Fig. 5 for two compared channel allocation schemes. The blocking probability using PRMA/FA starts to go up steeply at the point of offered traffic 0.06, while PRMA/DA at 0.12 approximately. From Fig. 5, it is observed that PRMA/FA has non-negligible blocking probability in the light loading range ($0.02 \sim 0.06$). This is expected since network access in PRMA/FA mainly depends on the current slot demand of the reserving stations. In this simulation, the VBR video source generates traffic corresponding to 16 cells per frame on average ($R_m = 16$). Thus total video traffic accounts for around 80% of total traffic. During the simulation, the video sources are observed to temporarily generate traffic at the rate of more than 100 slots per frame since their traffic fluctuates severely. Thus if a mobile station tries to attain network access during the period when all the slots serve the reserving stations and the period lasts longer than the maximum call setup time (W_{vmax}), the call will be blocked.

item	symbol	value
Frame length (msec)	T	6
Slot length (msec)		0.06
Number of slots (cells) per frame	N	100
PRMA/DA channel speed (Kbps)	R	7067
Voice codec data rate (Kbps)	R_v	64
CBR/VBR/ABR slot size (bytes)		53
Payload of a single slot (bytes)		48
Arrival rate (exponential) of new voice calls (calls/sec/user)	λ_v	$0.01 \sim 0.1$
Average length (exponential) of a voice call (min)	T_c	3
Maximum (fixed) voice call set up time(sec)	W_{vmax}	5
Video (VBR) frame rate		25
Average number of cells per video frame		104.8
Peak number of cells per video frame		220
arrival rate (exponential) of new ABR calls (calls/sec/user)	λ_d	$0.01 \sim 0.1$
Average message length (exponential) of ABR calls (Kbytes)	L	5.12

Table 1: Parameters used in simulation

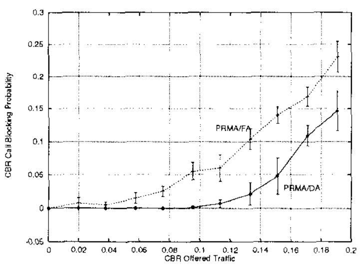

Figure 5: Voice call blocking probability versus voice call offered traffic

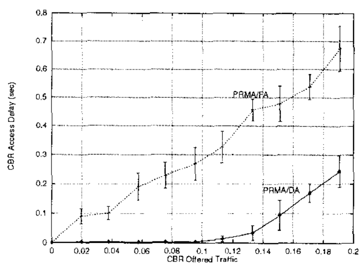

Figure 6: Voice call network access delay versus voice call offered traffic

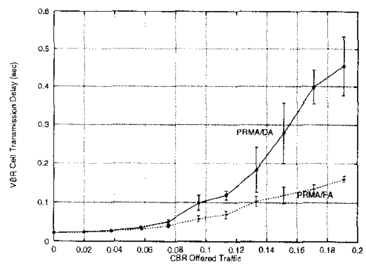

Figure 7: VBR video cell transmission delay versus voice call offered traffic

Figure 6 shows the curves of CBR network access delay versus CBR offered traffic for the two channel allocation schemes. The curves have a very similar shape when compared to the curves for blocking probability. That is, PRMA/FA shows relatively longer delay even at light load while PRMA/DA starts to undergo noticeable delay when the offered traffic reaches 0.13.

Figure 7 shows the VBR video cell transmission delay versus the offered CBR traffic. As shown in Fig. 7, a video cell experiences longer delay as higher loads are applied. The video cell of PRMA/FA has a gradual increase in delay while the PRMA/DA has a steep increase. Generally, as the CBR offered traffic increases, the PRMA/DA has more CBR reserving stations than PRMA/FA does due to PRMA/DA's advantageous way of accepting new calls. As more CBR stations enter the network, VBR reserving stations will lose more slots since CBR stations have a higher service priority. The performance of VBR stations can be improved if proper call admission control is applied.

4 Conclusion

In this paper, we have presented a new MAC protocol called PRMA/DA for wireless ATM LANs. PRMA/DA adopts a dynamic channel allocation scheme to cope with varying bandwidth demands for several classes of service, e.g., CBR, VBR and ABR. Furthermore, the ATM cell is employed as a basic transmission unit to provide seamless connectivity to a broadband ATM backbone network.

The results show that for a mixed traffic environment, PRMA/DA does achieve a significantly higher bandwidth efficiency over the static channel allocation scheme. The performance results also demonstrate that PRMA/DA provides expeditious network access and less blocking probability for the CBR user.

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