

A Performance Study of Multiple Access Control Protocols for Wireless Multimedia Services

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Abstract—The multiple access control (MAC) problem in a wireless network has intrigued researchers for years. For a broadband wireless multimedia network such as wireless ATM, an effective MAC protocol is very much desired because efficient allocation of channel bandwidth is imperative in accommodating a large user population with satisfactory quality of service. Indeed, MAC protocols for a wireless ATM network, in which user traffic requirements are highly heterogeneous (classified into CBR, VBR, and ABR), are even more intricate to design. Considerable research efforts expended in tackling the problem have resulted in a myriad of MAC protocols. While each protocol is individually shown to be effective by the respective designers, it is unclear how these different protocols compare against each other on a unified basis. In this paper, we quantitatively compare seven recently proposed TDMA-based MAC protocols for integrated wireless data and voice services. We first propose a taxonomy of TDMA-based protocols, from which we carefully select seven protocols, namely SCAMA, DT-DMA/VR, DTDMA/PR, DQRUMA, DPRMA, DSA++, and PRMA/DA, such that they are devised based on rather orthogonal design philosophies. The objective of our comparison is to highlight the merits and demerits of different protocol designs.

Keywords: Wireless multimedia services, wireless ATM, multiple access control, FDD, adaptive protocol, TDMA.

I. INTRODUCTION

The¹ classical design of a channel multiple access control (MAC) protocol is to arbitrate and statistically multiplex the transmission requests of multiple uncoordinated users and allocate transmission bandwidth to the users in a fair manner. Notorious examples include the ALOHA protocol for a packet radio network and the CSMA/CD protocol for a wired local area network. The key feature of the classic design is that all users are homogeneous—they have the same traffic characteristics. However, in our study, we consider a wireless ATM system for integrated isochronous and bursty services [10], [19], for which an effective and intelligent MAC protocol is particularly desired due to the sharing of the precious bandwidth by a dynamically changing population of users with various traffic demands. A MAC protocol for wireless ATM dis-

tinguishes itself from other MAC protocols in that various mechanisms are required to handle the diverse traffic demands of different services such as constant bit rate (CBR), variable bit rate (VBR), and available bit rate (ABR). CBR traffic such as voice telephony, VBR traffic such as video-conferencing, and ABR traffic such as file data have very different service requirements in terms of delay and loss tolerance, and throughput. Multiplexing these diverse services harmoniously such that reasonable QoS is maintained while at the same time maximizing the utilization of the precious channel bandwidth is a daunting and challenging task. Thus, while traditional ALOHA-type MAC protocols can handle homogeneous traffic efficiently, different techniques are needed for a wireless ATM system. As such, there are a plethora of efficient MAC protocols reported in the literature that are specially designed for wireless ATM [2], [3], [12], [16], [22]. In general, there are four aspects in characterizing these MAC protocols:

- *Request Mechanism:* The mechanism of receiving user requests critically affects the performance of a MAC protocol. For example, in some contention based protocols, too much contention (e.g., a large number of active users) will result in system instability such that users keep on contending without success due to excessive collisions. Under such a *thrashing* situation, most of the information slots are not used. Different protocols employ various techniques to combat this problem.
- *Slots Allocation:* In most MAC protocols, information slots are assigned on a first-come-first-basis and can be reserved in subsequent frames if the user is a voice terminal. However, some recently proposed protocols employ more intelligent approaches to further enhance the channel utilization.
- *Frame Structure:* Traditionally, the frame is of a static structure. That is, for example, there is a fixed portion of the frame dedicated for receiving transmission requests, while the remaining portion is for information slots. A major merit of a static frame structure is the ease of implementation and is energy efficient for the mobiles, which do not need to listen to the channel all the time. Some other protocols, however, employ a dynamic frame structure, with the objective to utilize the bandwidth more efficiently.
- *Performance:* The capacity of the network and quality of service (QoS) depend critically on the performance of the MAC protocol in terms of packet dropping rate, delay, throughput, and utilization.

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A scrutiny of the above four aspects reveals a large design space for MAC protocols. Indeed, based on these four dimensions, we introduce a simple taxonomy of recent MAC protocols suggested in the literature for wireless ATM. With the taxonomy, seven MAC protocols, designed based on radically different philosophies, are selected for an extensive performance comparison. The protocols chosen are:

- DQRUMA [8]: distributed queueing request update multiple access, a protocol that employs a novel piggybacking request update mechanism;
- DSA++ [17]: dynamic slot assignment, a protocol that is based on an intelligent slots allocation and scheduling mechanism;
- PRMA/DA [11]: packet reservation multiple access with dynamic allocation, a protocol that employs a novel dynamic frame structure;
- DTDMA/PR [18]: dynamic TDMA with piggyback reservation, a protocol that uses a dynamically adjust partitioning of information slots assigned for real-time (i.e., CBR or VBR) and non-real-time (i.e., ABR) users;
- DTDMA/VR [9]: dynamic TDMA with variable rate transmission, a protocol that uses an adaptive physical layer;
- DPRMA [4]: dynamic packet reservation multiple access, a protocol that uses a rate-controlled allocation strategy;
- SCAMA [15]: synergistic channel-adaptive multiple access, an adaptive protocol which works closely with the underlying physical layer in that through observing the *channel state information* (CSI) of each mobile user, the SCAMA protocol first segregates a set of users with good CSI from requests gathered in the request contention phase of an uplink frame. The SCAMA protocol then judiciously allocates information time slots to the users according to their traffic types, CSI, urgency, and throughput, which are collectively represented by a novel priority function.

We have implemented all the seven protocols on a common simulation platform, from which extensive performance results are obtained. The protocols are evaluated for test cases with and without request queues, which store transmission requests that survive the contention but fail to get assigned information slots. Three performance metrics, namely cell loss rate, ABR data delay, and ABR data throughput, are considered. The balance of this paper is as follows. In Section II, we present a detailed scrutiny of the TDMA-based MAC problem, with the help of a simple taxonomy. We then delineate the key features of the selected protocols in Section III. Section IV contains the performance results and our interpretations. The final section provides some concluding remarks.

II. MAC PROTOCOLS FOR WIRELESS ATM

As tetherless communication and computing becomes more and more ubiquitous, one of the most important issues in a cellular wireless network is how to effectively manage the precious bandwidth so as to support a large and dynamic user population with a reasonable level of service quality. The abundant bandwidth available in a broadband wireless systems does not help to alleviate the

problem because the user population size will for sure increase proportionately. Thus, bandwidth management problems, having baffled researchers for years, continue to be a rich land of research. The goal of a MAC protocol is to judiciously arbitrate the transmission requests of multiple uncoordinated users and assign transmission bandwidth to the users. While the MAC problem also exists in wired networks, a MAC protocol in a wireless communication system is particularly important due to the sharing of the precious bandwidth by a dynamically changing population of users with various traffic demands. Indeed, the dynamic nature of users population, both spatially and temporally, makes the capacity of the network and quality of service depend critically on the performance of the MAC protocol in terms of packet dropping rate, delay, and throughput.

Figure 1 depicts a partial taxonomy of TDMA based MAC protocols for wireless ATM considered in our study. In a TDMA-based protocol, time is divided into slots, which are grouped into frames. The slots, more specifically the information slots, are for users to transmit information packets. In general, the users contend for information slots on a frame-by-frame basis. There are two types of TDMA-based protocols: pure TDMA and *dynamic* TDMA (DTDMA). In a pure TDMA protocol, the slots assignment, determined statically, is fixed throughout the communication process without regard to the actual requirements of the users. Thus, even if a user does not have any information packet to send, the assigned time slot is still occupied and, therefore, is wasted. In view of the poor utilization and inflexibility, pure TDMA protocols are not used in the cellular wireless networks considered in this paper, due to the dynamic users population involved. DTDMA protocols can be classified as TDD (time division duplex) or FDD (frequency division duplex) based. A TDD based protocol (e.g., the MDR-TDMA protocol [7], [19]) can exploit the asymmetry between the uplink (heavily loaded) and downlink (lightly loaded) communications in that the bandwidth for downlink communication can be converted for uplink communication when mobile traffic load is high. However, a TDD based system suffers from the long and irregular delay in both the uplink and downlink communications. A FDD scheme, by contrast, can exploit the almost instantaneous acknowledgment (i.e., short propagation delay) in both uplink and downlink transmissions, and as such, the interface design is also simpler. We focus on FDD schemes only in this paper.

Time on the FDD based uplink channel is also divided into a contiguous sequence of TDMA frames, which are subdivided into request slots and information slots. The information slots are sometimes further classified into CBR/VBR and ABR slots. There are two types of packets being transmitted in the channel, namely the *request packet* and the *information packet*. A request packet is used for the request of information slot (for carrying CBR, VBR, or ABR data cells). However, most earlier protocols do not distinguish slots for transmitting request or information data, as in the classical PRMA protocol [5] (see Figure 2(a)). Indeed, these protocols use also the information slot for requests contention, and as such, the bandwidth utilization can be low if traffic load is high. Some more recently proposed protocols partition the TDMA

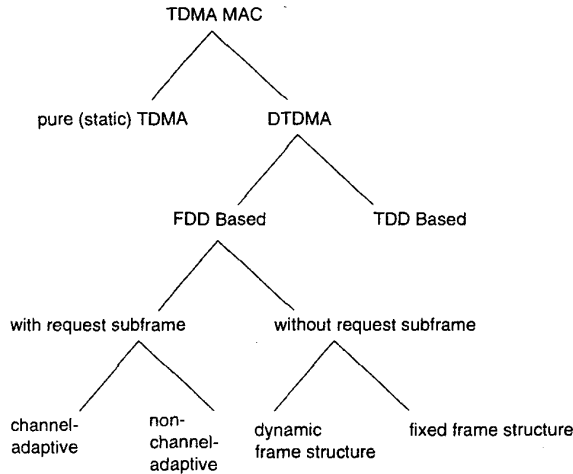


Fig. 1. A taxonomy of TDMA-based MAC protocols for wireless ATM.

frame into two parts: *request subframe* and *information subframe*, as shown in Figure 2(b). The motivation of this approach is that a request packet often includes only very small amount of information, namely the origin and the destination addresses, and is therefore usually much shorter than a information packet. The request subframe, therefore, can be operated with a much shorter slot duration using the slotted-ALOHA protocol.

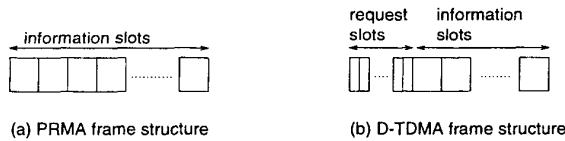


Fig. 2. Frame structures of (a) the classical PRMA protocol, (b) a generic DTDMA protocol.

MAC protocols can be further classified into two categories: dynamic frame structure and fixed frame structure. In the former category, the frame structure, in terms of frame length or frame format, is varied over time. The objective is to optimize the bandwidth usage for requesting and information transmission. Finally, in the fixed frame structure category, some recently proposed protocols (e.g., DTDMA/VR and SCAMA) use a variable-throughput frame supported by a channel adaptive physical layer. Such channel adaptive protocols are motivated by the fact that, in general, previous protocols attempt to accommodate more data users, which do not impose constraints on data delay, by exploiting the silence gaps of the CBR/VBR users, which require bounded-delay packet transmission and hence, enjoy a higher transmission priority than ABR users in that reservation is allowed for the former but not the latter. However, while sophisticated slot allocation strategies with articulated frame structures are proposed in these methods, most of them considers the effect of burst channel errors on protocol performance, let alone the investigation of exploiting the error characteristics to enhance performance. Essentially, these previous protocols are designed and an-

alyzed based on the assumption that packet transmission through the wireless channel is error-free. Indeed, because the geographically scattered mobile users inevitably suffer from different degrees of fading and shadowing effects, a common drawback of previous MAC protocols is that they assume the underlying physical layer always delivers a constant throughput, and as such, they may not be able to effectively utilize the precious bandwidth when the channel condition is swiftly varying among different users.

III. PROTOCOL DESCRIPTIONS

From the taxonomy shown in Figure 1, seven recent protocols are selected for our quantitative comparison, with the objective to highlight the merits and demerits of different protocol designs. The protocols selected and their distinctive characteristics are listed in Table I, which includes the key aspects: Request Sub-Frame (RSF), Dynamic Frame (DF), and Prioritization. For completeness, the operation of these protocols are outlined below. The reader is referred to the respective references for more detailed information.

TABLE I
PROTOCOL CHARACTERISTICS.

Protocol	RSF	DF	Priority
DQRUMA	No	Yes	-
DSA++	Yes	No	CBR
PRMA/DA	No	Yes	CBR
DTDMA/PR	Yes	No	CBR
DTDMA/VR	Yes	No	-
DPRMA	No	No	VBR
SCAMA	Yes	No	CBR/VBR

A. DQRUMA

The DQRUMA (distributed queueing request update multiple access) protocol proposed by Karol, Liu, and Eng [8] is a well known MAC protocol for wireless ATM. In simple terms, being a FDD (frequency division duplex) protocol, DQRUMA works by dividing the uplink frame into two sections with the first section for requests contention, whereas the second section for information data transmissions. A nice and novel feature of the DQRUMA protocol is the use of a piggyback reservation field, with which a VBR user can update the traffic slot demand without the need of an extra contention. Another novel feature of the DQRUMA protocol is that if needed, the base-station can convert one information slot into a number of request slots so as to alleviate the contention. However, despite that the dynamic frame structure and piggybacking mechanism are useful for better channel utilization, the DQRUMA protocol suffers from the lack of an intelligent slots allocation strategy. Thus, the QoS of different users (CBR, VBR, and ABR) are not optimized.

B. DSA++

The DSA++ (dynamic slot assignment) protocol proposed by Petras and Kr mbling [17]. The DSA++ protocol employs a variable-length frame structure called a signaling burst, in which a mobile user can reserve information time slots in the uplink frame by using the reservation slots in the uplink reservation phase. To handle the heterogeneous QoS requirements, the assignment of information time slots is performed by a scheduler in the base-station, which uses a priority function composed of the number of pending cells and the deadlines. The priorities are assigned such that priorities between classes are constrained by the relationship: $CBR > VBR > ABR$. The strength of the DSA++ protocol is its comprehensive prioritization process.

C. PRMA/DA

The PRMA/DA (packet reservation multiple access with dynamic allocation), proposed by Kim and Widjaja [11], is an enhanced version of the PRMA protocol [5]. Basically, the PRMA protocol is extended to allow VBR users to make rate-based reservations. A novel feature of the PRMA/DA protocol is that the dynamic framing mechanism, in which the base-station adjusts the relative proportions of request slots and information slots according to the extent of request contention. For example, if the base-station detects a collision in a certain request slot, it infers that there are at least two mobiles contending for a request slot, and as such, in the next frame, one more request slot will be added. On the other hand, if the base-station finds that a certain request slot is unused, one request slot will be converted to an information slot in the next frame. This dynamic framing mechanism can enhance the stability as well as utilization of the system. However, since a full information slot is used for requesting also, the bandwidth wastage can be significant.

D. DTDMA/PR

Similar to DQRUMA, the DTDMA/PR (dynamic TDMA with piggyback reservation) proposed by Qiu, Li, and Ju [18] also allows VBR users to update time slots requirements using a piggyback field in an uplink information slot. A distinctive feature of DTDMA/PR is that the information slots are classified as long-term and short-term reservable. Specifically, long-term slots are for CBR and VBR users, while short-term ones are for ABR users.

E. DTDMA/VR

The DTDMA/VR (dynamic TDMA with variable rate transmission) [9] protocol employs a static frame structure in that the time frame is divided into two parts: N_r request slots and N_i information slots. Specifically, a traditional slots assignment strategy is used in that whenever a request is successfully received in the request phase, information slots, if any, are immediately assigned to the requests. The DTDMA/VR protocol also considers the effect of burst errors by employing a channel adaptive physical layer. However, in contrast to the proposed SCAMA protocol, the DTDMA/VR does not consider

the synergistic interaction between the MAC and physical layers and therefore, it is not a fully adaptive protocol. In other words, the MAC layer is not aware of the current situation in the physical layer in the process of bandwidth allocation. However, with the help of the channel-adaptive physical layer, DTDMA/VR has twice the average offered throughput compared to previous protocols [14].

F. DPRMA

The DPRMA (dynamic packet reservation multiple access) protocol proposed by Dyson and Haas [4]. Information time slots within a DPRMA frame are partitioned among the mobiles based on the amount of slots required by each user. Mobile users may reserve a number of slots within a frame or even slots in alternating frames, as long as there is frame capacity. However, if capacity is not enough, users are required to share the deficit proportionately. In contrast to the DSA++ protocol, DPRMA gives a slightly higher priority to VBR users. Specifically, the DPRMA protocol uses a rate-controlled approach in that slots allocation is based on the relative bandwidth requirements among the users. However, when traffic load is high so that there are not enough information slots, the users are required to share the deficit proportionately according to their rate requirements.

G. SCAMA

The SCAMA (synergistic channel-adaptive multiple access) is recently proposed by us [15] and is based on a novel concept—exploiting the synergy between two protocol layers instead of strictly following the traditional information hiding protocol design paradigm. Figure 3 highlights the differences in the designs among a traditional fixed throughput MAC protocol (denoted generically as DTDMA/FR), DTDMA/VR, and SCAMA.

As indicated earlier, most of the previous schemes, bandwidth allocation in the MAC layer for a certain traffic type is essentially based only on a first-come-first-serve strategy. Some of the previous MAC schemes even do not consider CBR and VBR separately. For those MAC schemes that treat CBR, VBR, and ABR separately, no mechanism is incorporated to adjust the priority between classes in a flexible way. Most importantly, these protocols do not take into account of the CSI in the bandwidth allocation process. However, in a wireless communication system where burst errors due to fading are inevitable, CSI is a critical factor in achieving a higher overall utilization of the precious bandwidth in the system. This motivates the SCAMA protocol, which works closely and synergistically with the underlying channel adaptive physical layer. Specifically, the protocol adaptively assigns information slots to users based on their CSI ranking. Furthermore, the SCAMA protocol could accommodate CBR, VBR, and ABR traffic effectively with a very flexible priority adjustment between different classes. The frame structures of the SCAMA protocol are detailed in [15].

The operation of the SCAMA protocol is divided into two phases, namely the *request phase* and *transmission*

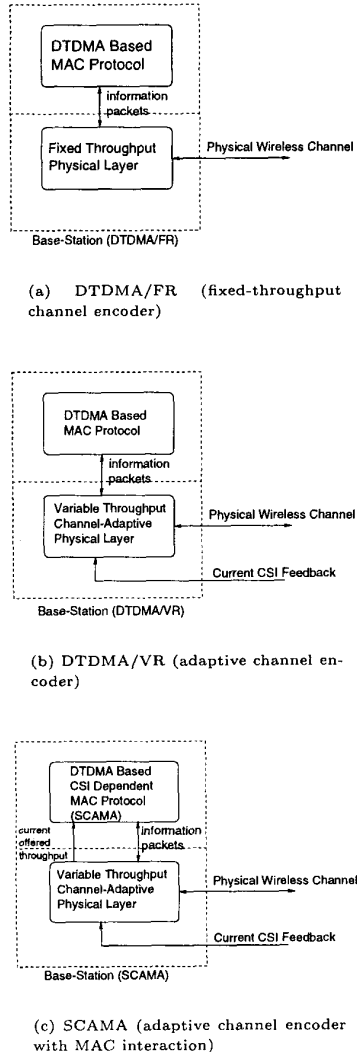


Fig. 3. Conceptual models of the physical and MAC layers.

phase. In the request phase, mobile terminals which have packets to transmit will send a request packet in one of the N_r request mini-slots, governed by the respective permission probability. The request packet is very short (24 bits), occupying only a mini-slot. It contains the mobile terminal ID, request type (CBR, VBR, or ABR), data deadline, number of information data cells desired to transmit as well as pilot symbols for CSI estimation. If more than one mobile terminals send request packets in the same request mini-slot, collision occurs and all the request packets are lost if capture effect is not considered (if capture is considered, the request with the highest signal energy may be successfully received). After each request mini-slot, an acknowledgment packet will be broadcast from the base-station through the acknowledgment mini-slot in the downlink frame. The acknowledgment packet

contains only the successful request packet ID. Mobile terminals that fail to receive an acknowledgment will retransmit the request packet in the next request mini-slot, again governed by the permission probability. On the other hand, successfully acknowledged users will wait for announcement on the allocation schedule of the traffic slots from the base-station.

Unlike traditional MAC protocols, the base-station will collect all requests in the current request phase as well as the *backlog requests* from the previous frames before allocation of traffic slots. All the requests will be assigned priorities according to the deadline, CSI, service type (CBR, VBR, or ABR), as well as the waiting time of the request (i.e., the number of elapsed frames since the request is acknowledged). Since the physical layer offers a variable throughput which is dependent on the CSI, the rationale behind the SCAMA MAC protocol is to give higher priority to the mobile terminals that are in better channel condition in the bandwidth allocation process. The motivation of this strategy is that a user with better channel condition, with the support of the variable rate channel encoder, can enjoy a larger throughput and therefore, can use the system bandwidth more effectively. Nevertheless, for fairness's sake, information slots should also be allocated to mobile terminals that are approaching their deadlines, despite their possibly worse channel states; otherwise, the queued information packets will be dropped. The queue is maintained by using priority functions capturing the relative importance of requests in terms of deadline, CSI, and traffic type [15].

IV. RESULTS AND INTERPRETATIONS

In this section, we present the performance results of our performance comparison of the seven protocols. In our simulation study, we assume a transmission bandwidth of 1.36 MHz for the TDMA frames. CBR bit rate is 8 kbps while the average VBR bit rate is 128 kbps. Table II summarizes the parameters we used.

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
N_r	10
N_i	40
N_b	20
t_t	1000 msec
t_s	1350 msec
p_c	0.3
p_v	0.3
p_a	0.2
channel bandwidth	1.36MHz
CBR (voice) data rate	8 kbps
VBR (video) data rate	128 kbps
ABR data rate	16 kbps
number of simulated frames	2×10^6

A. Source Models

The wireless ATM system considered in this paper is aimed to support integrated CBR, VBR, and ABR services. As such, we assume that there are only three types of mobile terminals, namely the CBR terminal, the VBR terminal and the ABR terminal in the system. Both CBR and VBR cells are assumed to be delay sensitive while ABR cells are assumed to be delay insensitive. Thus, CBR and VBR cells are labeled with *deadlines*. The cells will be dropped by a mobile terminal if the deadline expires before being transmitted. Such cells dropping has to be controlled to within a certain limit (e.g., below 1% for voice as indicated in [6]) in order to have acceptable quality of service for CBR and VBR users. The source and contention models are summarized below.

- **CBR Source Model:** We use voice as an example CBR source. The voice source is assumed to be continuously toggling between the talkspurt and silence states. The duration of a talkspurt and a silence period are assumed to be exponentially distributed with means t_t and t_s seconds, respectively (as indicated by the empirical study in [18], $t_t = 1$, and $t_s = 1.35$). We assume a talkspurt and a silence period start only at a frame boundary. Finally, as mentioned above, a voice source cannot tolerate a cell loss rate higher than 1% in order to achieve a reasonable service quality [6].

- **VBR Source Model:** We use video teleconference as an example VBR source. In the model we use [13], the number of cells per VBR period (i.e., 40 msec for a 25 fps frame rate) is governed by the DAR(1) model, which is a Markov chain characterized by three parameters: the mean, the variance, and ρ . The transition matrix is computed as:

$$P = \rho I + (1 - \rho)Q \quad (1)$$

where ρ is the autocorrelation coefficient and I is the identity matrix. Furthermore, each row of Q is identical and consists of the negative binomial probabilities (f_0, \dots, f_K, F_K) , where $F_K = \sum_{k < K} f_k$, and K is the peak rate. Similar to a voice source, a video source can only tolerate a 1% cell loss rate [13].

- **ABR Source Model:** The arrival time of data generated by a ABR data terminal is assumed to be exponentially distributed with mean equal to one second. The data size, in terms of number of cells, is also assumed to be exponentially distributed with mean equal to 100 cells. An ABR user will not drop cells because there is no deadline constraint. Again we assume that the cells arrive at a frame boundary.

- **Terminal Contention Model:** As in most previous studies, to avoid excessive collisions, even if a user has some cells awaiting to be sent, the user will attempt to send a request at a request mini-slot only with a certain *permission probability*. The permission probability for CBR, VBR and ABR users are denoted by p_c , p_v and p_a , respectively. The protocol also has a *request queue* which stores the previous requests that survive the contention but are not allocated information slots.

It is also interesting to investigate the performance of the seven protocols under situations with and without capture. Thus, the capture process is also implemented. Specifically, suppose there are k requests, with signal power denoted by P_1, P_2, \dots, P_k , contending for a request

mini-slot. A request j can be captured if [1]:

$$\frac{P_j}{\sum_{i \neq j} P_i} > \gamma$$

where γ is the SNR threshold.

A.1 CBR Performance

The service quality for CBR users, being voice sources, is governed by the average cell loss rate, P_{loss} , which is contributed by two factors: cell dropping at the mobile and cell loss during transmission. On one hand, voice cell is delay sensitive and hence, voice cells are labeled with deadlines. A voice cell has to be discarded if its delay exceeds the deadline². Such discarding constitutes the cell dropping at the voice terminal. On the other hand, transmitted cells could be corrupted due to channel error and thus, cell transmission error results. The cell loss rate P_{loss} is then given by:

$$P_{loss} = \frac{N_{tx} - N_{rv}}{N_{tx}} \quad (2)$$

where N_{tx} and N_{rv} are the number of transmitted voice cells and the number of voice cells received without error, respectively.

Figure 4 shows the cell loss rate performance of the seven protocols for the CBR users. In this set of experiments, we varied the number of CBR users in the system, while we fixed the number of ABR users to be 25 and that of VBR users to be 20 and 25 also. Consider the results shown in Figure 4(a). As can be seen, the DPRMA protocol performs much worse compared with the other protocols. The DPRMA protocol cannot even handle as few as 10 CBR users. Indeed, the DPRMA protocol was found to perform well in the range of a few VBR users, as demonstrated in [4]. The DSA++, DQRUMA, and DT-DMA/VR protocols in general perform better than the DPRMA protocol. However, the cell loss rates achieved in these three protocols are still much higher than the 1% tolerance threshold for a CBR (voice) user. This can be explicated by the fact that the DQRUMA and DTDMA/VR protocols do not incorporate any prioritization mechanism in the time slots allocation process. That is, the time slots are essentially allocated in a first-come-first-serve manner. Thus, as VBR and ABR users usually have a much larger chunk of cells for transmission, the CBR users suffer from the "convoy" effect (i.e., a large request blocks a number of subsequent small requests), and thus, cell droppings occur quite frequently. In addition, among these three protocols, the DQRUMA is the least stable. Indeed, when the number of CBR users reaches 150, the protocol exhibits some thrashing effect—users keep contending with actually transmitting. On the other hand, the PRMA/DA, DTDMA/PR, and the SCAMA protocols perform much better than the former four protocols. The cell loss rate is two order of magnitude lower. Note that these three protocols allocate slots according to the requests' priorities. In particular, isochronous users such as CBR and VBR users

²In this paper, the deadline of voice cell is assumed to be 20 msec after it is generated by the source.

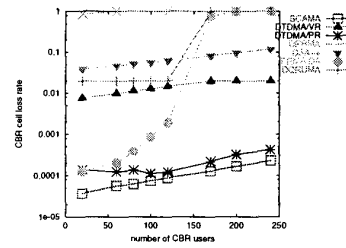
are given a higher priority than the ABR users. Thus, the results indicate that the priority functions used in these protocols are superior to those used in the former four protocols. Furthermore, the channel adaptive protocol performs the best because the cell loss due to dropping can be avoided almost completely by the intelligent slots allocation algorithm. The ranking of the protocols for CBR users is: SCAMA, DTDMA/PR, PRMA/DA, DTDMA/VR, DQRUMA, DSA++, DPRMA. Finally, we can see that for all seven protocols, including more VBR users in general slightly lowers the capacity of the system. The capture effect in general makes the protocols more stable even for high load.

A.2 VBR Performance

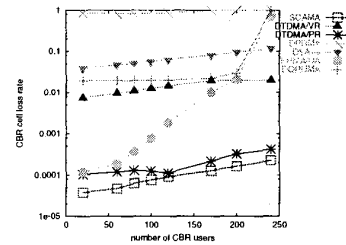
Similar to CBR users, the service quality of VBR users is also sensitive to loss (e.g., the image quality degrades if some cells are lost in a video-conferencing application). Also, being an isochronous source, cells have deadlines such that missing the transmission deadlines render the cells useless. Thus, we also evaluate the performance of the protocols using the cell loss rate for VBR users. Figure 5 depicts the VBR cell loss rate performance of the seven protocols for cases with 25 ABR users and 30/50 CBR users. We can see that in contrast to CBR performance, the DTDMA/PR protocol performs quite poorly for VBR users in that the cell loss rate is much higher than the 1% threshold even for 5 VBR users. This phenomenon is a result of assigning higher priority to CBR users in the DTDMA/PR, which concurs with the results presented in [18]. The DQRUMA, DPRMA, DSA++, and PRMA/DA protocol also gives similar performance as the DTDMA/PR protocol. The DTDMA/VR protocol, however, outperforms these five protocols by a large margin for VBR users. This is because the variable-throughput physical layer offers almost two times the average throughput compared with traditional fixed-throughput physical layers and is reflected in the performance of DTDMA/VR. Finally, we can see that the SCAMA protocol considerably outperforms the DTDMA/VR protocol. This illustrates the synergy that could be achieved by the judicious requests prioritization (based on CSI, urgency, and throughput) process in the former. Also, in contrast to the CBR performance, the capture effect only slightly improves the performance of protocols. The remaining VBR results show a similar trend.

A.3 ABR Performance

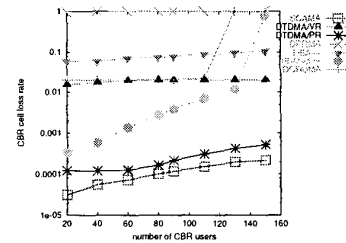
ABR cells are delay insensitive and as such, they will not be discarded at the mobiles. However, ABR cells may experience transmission errors when the channel condition is poor. Thus, lost cells are retransmitted (through the data-link layer). This inevitably introduces additional delay due to retransmissions. Here, different from CBR and VBR users, ABR users' performance is quantified by two measures: delay and throughput. The average ABR data throughput, $\bar{\rho}$, is defined as the average number of cells successfully received at the base-station per frame. The average delay, \bar{D}_d , is defined as the average time that a cell spends waiting in the transmitter buffer



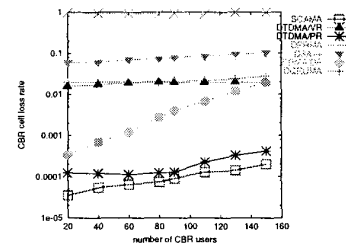
(a) 25 ABR users and 20 VBR users (without capture)



(b) 25 ABR users and 20 VBR users (with capture)

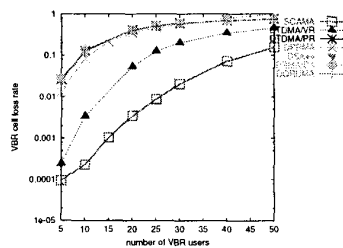


(c) 25 ABR users and 25 VBR users (without capture)

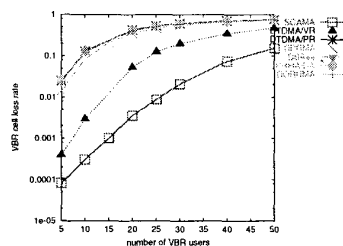


(d) 25 ABR users and 25 VBR users (with capture)

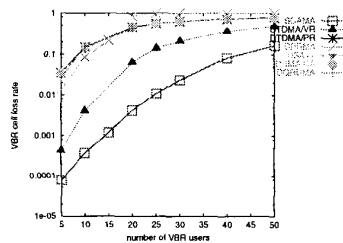
Fig. 4. Performance of the protocols for CBR users.



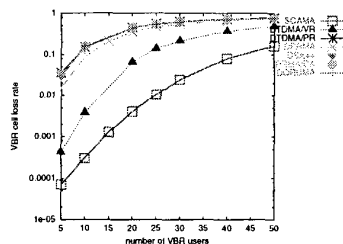
(a) 25 ABR users and 30 CBR users (without capture)



(b) 25 ABR users and 30 CBR users (with capture)



(c) 25 ABR users and 50 CBR users (without capture)



(d) 25 ABR users and 50 CBR users (with capture)

Fig. 5. Performance of the protocols for VBR users.

until the beginning of the successful transmission. Figures 6 and 7 illustrate the performance of data terminal in terms of \bar{D}_d and $\bar{\rho}$, respectively, for cases with 5/10 VBR users and 20 CBR users. When the traffic load is high, the system is in a highly congested state so that the average per-user throughput drops and the average per-user delay also increases dramatically. These adverse phenomena are detrimental to the data users' quality of service (QoS), which depends critically on the parameters pair (delay, throughput) as describe above. Before the system gets into the congested state, the SCAMA protocol consistently offers a much lower delay and a much higher throughput compared to the other three protocols. In other words, given a certain QoS level, the SCAMA protocol can support a much larger ABR user population. For example, at a QoS level of (1 sec, 0.25), the SCAMA protocol can support more than 300 ABR users (see Figure 6(a)) while the second best protocol, the DTDMA/VR protocol, can only support 100 ABR users. Finally, as in the case of VBR, the capture effect does not help much. The other results give similar observations.

B. Interpretations

From the simulation results shown above, the SCAMA protocol is robust and outperforms six recently proposed efficient protocols by a considerable margin. In this section, we further provide some interpretations of the performance results.

- Protocols using a more comprehensive allocation strategy perform better. For example, in the DSA++, DTDMA/PR, and SCAMA protocols, the prioritization process which takes into account the important factors such as throughput required and urgency. The SCAMA protocol outperforms the others because one more important factor, namely the channel condition, is also considered.
- Capture effect does not help improving the performance of protocols. This indicates that the performance bottleneck is in the allocation of information slots, rather than the resolution of requests contention.
- In view of the superior performance of both the DTDMA/VR and SCAMA protocols, using a variable throughput adaptive physical layer seems to be a mandatory consideration in future MAC protocol design. The rationale is that as burst errors are unavoidable and are time-varying in a rather predictable manner (e.g., Rayleigh), exploiting the channel condition using a dynamic approach (i.e., varying the instantaneous throughput), instead of a static one (e.g., incorporating large amount of FEC statically and relying on ARQ), is much more efficient.
- A CBR terminal may experience a deep fading for a long time when it is affected by shadowing. In the other protocols (including DTDMA/VR), bandwidth allocation in the MAC layer is carried out regardless of the current channel condition as detected in the physical layer. Thus, information slots could also be allocated to such a user and the transmitted packets will be very likely lost due to the poor channel condition. In other words, assigned slots are simply wasted. This kind of wasteful allocation is avoided in the SCAMA protocol.
- Selection diversity is implicitly incorporated in the SCAMA protocol. Through the priority-based assign-

ment process, every frame is packed with a selected group of information cells with good channel states. Thus, the effective delivered throughput per frame achieved in SCAMA can be much higher than that in DTDMA/VR and other protocols. In SCAMA, a large number of transmission requests are collected first before allocation of information slots. From the collection of requests, there is a high likelihood that a sufficient number of requests with good channel states can be selected to fully utilize the information slots in an effective manner (i.e., high throughput). For those requests with poor instantaneous channel states, their transmissions are deferred until when the CSI improves or the deadlines are approaching. By contrast, in the DTDMA/VR and DQRUMA protocols, requests are served in a first-come-first-serve manner due to the traditional strategy of immediately assigning slots upon successful receipt of requests. Thus, the channel states of such requests are highly diverse and, most importantly, some requests with bad channel states (hence very low throughput) are also served, whereby causing inefficient bandwidth utilization. For example, a CBR terminal may experience a very good CSI for a long time (out of shadowing). In protocols without considering CSI in the prioritization process (DTDMA/PR) or those even without explicit prioritization (DTDMA/VR and DQRUMA), this user, however, may fail to successfully transmitted a request to the base-station, probably because of excessive collisions in the request phase. In comparison, the SCAMA protocol gathers a large number of requests through successive frames, and allocate time slots to the users that can use the system bandwidth more effectively. Thus, the likelihood of "missing" a user with good channel state is much lower and the utilization of bandwidth is therefore higher.

V. CONCLUSIONS

We have presented an extensive performance comparison of seven recently proposed MAC protocols, namely SCAMA, DPRMA, DTDMA/VR, DTDMA/PR, PRMA/DA, DSA++, and DQRUMA. Using our proposed taxonomy of TDMA-based MAC protocols, these FDD based protocols are carefully selected such that they are devised based on rather orthogonal designed philosophies. The protocols are extensively evaluated for test cases with and without capture. Our simulation results reveals that using a variable-throughput physical layer (in the SCAMA and DTDMA/VR protocols) can help reducing voice packet dropping due to transmission errors. Finally, in view of the fact that the SCAMA protocol outperforms the other six protocols in terms of CBR/VBR cell loss rate, ABR throughput and delay, all by a considerable margin, the knowledge of the channel condition reported to the MAC layer by the physical layer (in the SCAMA protocol) is indeed a very useful component in achieving even higher performance in a wireless communication system where burst errors are the norm rather than exception.

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