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Efficient multiple access control using a channel-adaptive protocol for a wireless ATM-based multimedia services network

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Abstract

As tetherless multimedia computing environments are becoming much desired, broadband wireless communication infrastructures such as wireless ATM will play an important role and thus, are expected to proliferate. However, despite much research efforts have been expended, the multiple access control of the precious bandwidth remains a challenging problem because of the existence of two common drawbacks in state-of-the-art protocols: (1) channel condition is ignored or not exploited, and (2) inflexible or biased time slots allocation algorithms are used. Indeed, existing protocols mostly ignore the burst errors due to fading and shadowing, which are inevitable in a mobile and wireless communication environment. A few protocols take into account the burst errors but just "handle" the errors in a passive manner. On the other hand, most of the existing protocols employ an inflexible or biased allocation algorithm such that over-provisioning may occur for a certain class of users at the expense of the poor service quality received by other users. In this paper, a new judicious MAC protocol, called SCAMA (synergistic channel adaptive multiple access) is proposed. The proposed protocol works closely with the underlying physical layer in that through observing the channel state information (CSI) of each mobile user, the MAC protocol first segregates a set of users with good CSI from requests gathered in the request contention phase of an uplink frame. The MAC protocol then judiciously allocates information time slots to the users according to the respective traffic types, CSI, urgency, and throughput, which are collectively represented by a novel and flexible priority function. Extensive simulation results indicate that the protocol is robust and considerably outperforms previous protocols.

Keywords: Mobile computing; Wireless ATM; Multiple access control; Adaptive protocol

1. Introduction

One of the most important problems in the design of a mobile computing environment based on the wireless ATM infrastructure (see Fig. 1) is the multiple access control (MAC) of the wireless channel. A high-quality MAC protocol can greatly enhance the capacity and quality of service (QoS) of the mobile users in the system. However, designing such a MAC protocol has proven to be a challenging task as indicated in the number of different protocols suggested in the literature in the past few years [1,10]. One distinctive requirement for a wireless ATM MAC protocol is that, in contrast to traditional telecommunication MAC protocols (e.g. ALOHA), the MAC protocol has to accommodate a highly heterogeneous population of users. Specifically, the users in the system can be classified 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. Satisfying the diverse QoS requirements of these different user classes is beyond doubt non-trivial. A few recently proposed protocols attempt to meet the challenge of providing efficient MAC support in wireless ATM systems. One well-known example is the DSA++ protocol proposed by Petras and Krämling [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. Another recently proposed protocol is the DPRMA protocol proposed by Dyson and Haas [5]. Information time slots within a DPRMA frame are

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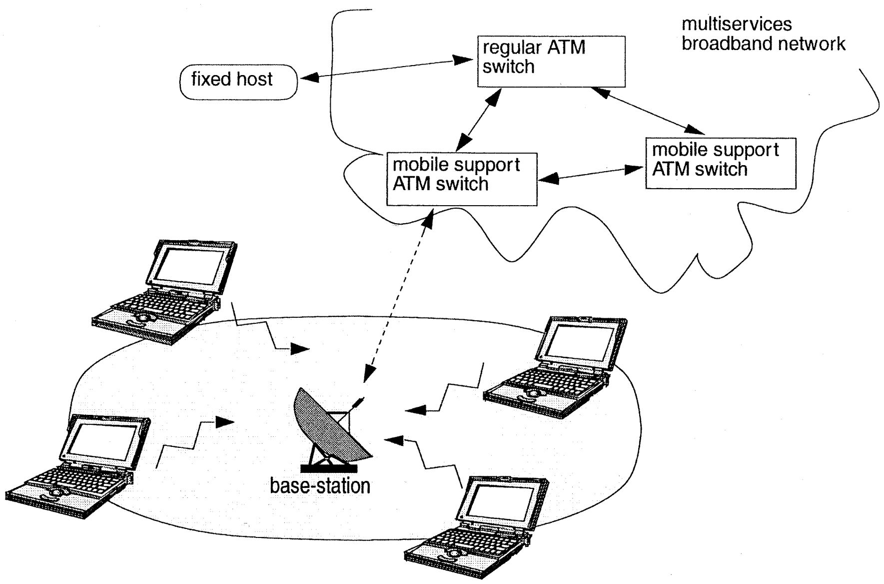

Fig. 1. Broadband mobile computing environment based on wireless ATM.

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.

From above the brief summary of the two previous protocols, it is evident that some sort of prioritization mechanism has to be incorporated in the MAC protocol in order to efficiently utilize the channel bandwidth while at the same time satisfying the heterogeneous and dynamic user requirements. However, despite that these recent MAC protocols are shown to be able to handle the diverse service requirements, such protocols still have a number of common drawbacks. Firstly, while sophisticated slot assignment strategies with articulated frame structures are proposed in these methods, none of them considers the effect of burst channel errors on protocol performance, not to mention the investigation of exploiting the error characteristics to enhance performance. Essentially, these previous protocols are designed and analyzed based on the assumption that data transmission through the wireless channel is error-free. However, because the geographically scattered mobile users inevitably suffer from different degrees of *fading* and *shadowing* effects, burst errors are in fact the norm rather than the exception. Furthermore, as the time-varying channel conditions (hence, the burst errors) are governed by the two statistical phenomena, which are quite well understood, the channel state information (CSI) can actually be exploited to further enhance the protocol performance. The second common drawback is that the slot allocation methods are quite inflexible in that these previous protocols are designed to optimize the performance of VBR and/or CBR users only. This lack of fairness control may lead to starvation of ABR users. Furthermore, over-provisioning becomes inevitable in these protocols. Thirdly, an important QoS metric, namely the delay jitter, is usually ignored and the protocol performance in this aspect is unknown. In view of these drawbacks, in this paper a new FDD-based MAC protocol for wireless ATM is proposed with the following distinctive features:

- The proposed MAC protocol works closely with the underlying physical layer in that through observing the channel state information (CSI) of each mobile user, the MAC protocol first segregates a set of users with good CSI from requests gathered in the request contention phase of an uplink frame. The MAC protocol then judiciously allocates information time slots to the users according to the respective traffic types, CSI, urgency, and throughput, which are collectively represented by a novel priority function.
- The priority function used in the proposed MAC protocol is designed to be very flexible to dynamically adjust the relative priorities of different users, both within and between traffic classes.
- Furthermore, the proposed protocol can also minimize the delay jitter of user transmissions.

Traditional physical layer delivers a constant throughput in that the amount of error protection incorporated into a packet is fixed without regard to the time varying channel condition. However, the design proposed in the present paper is a channel-adaptive one in that a variable throughput channel adaptive encoder and modulator are used in the physical layer [12,14]. Specifically, a low capacity feedback channel is employed to convey estimated channel state

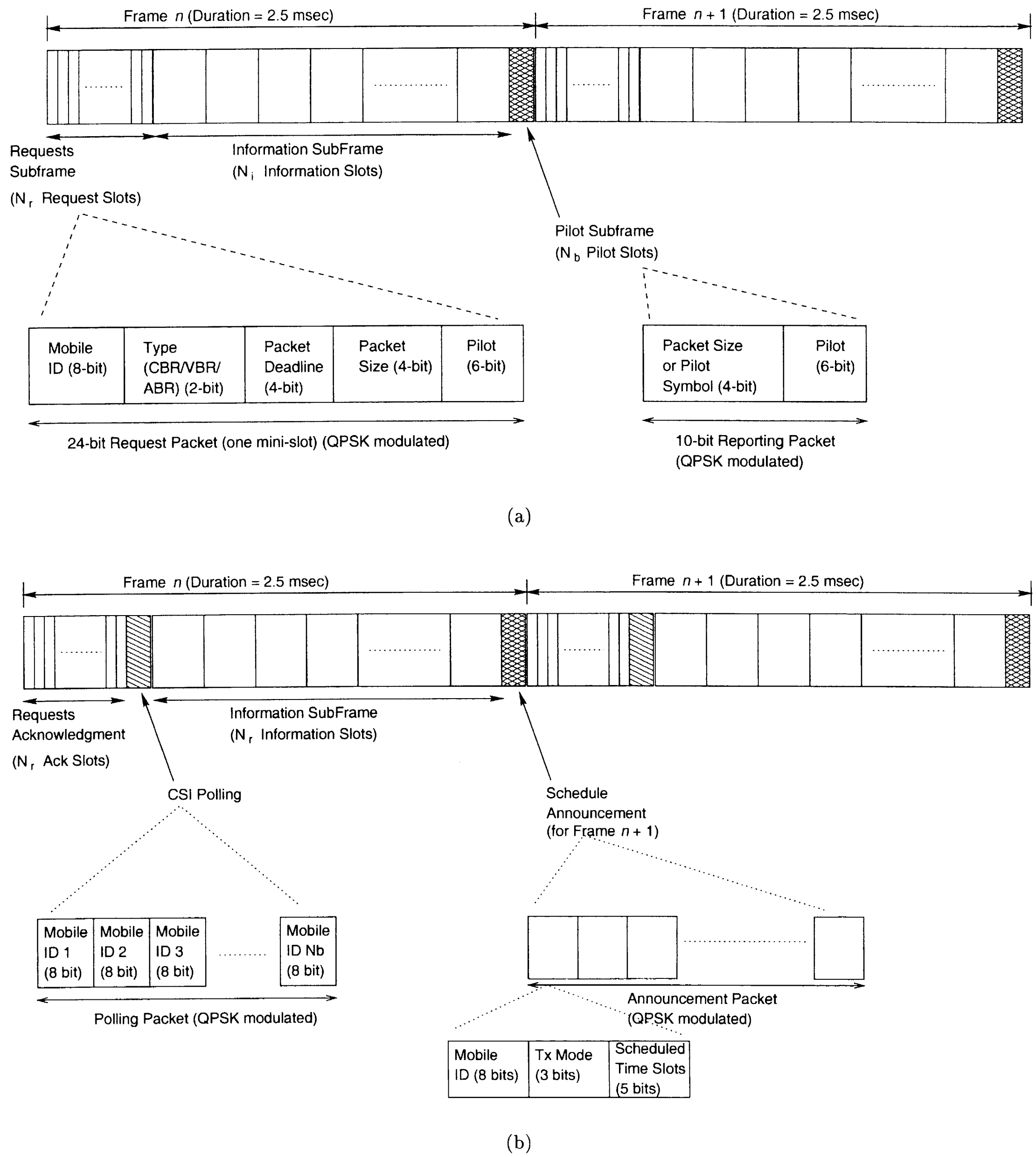

Fig. 2. Frame structures of the proposed SCAMA protocol for CBR, VBR, and ABR users.

information (CSI) to the transmitter. Thus, under good channel condition (i.e. signal attenuation is low), the amount of protection incorporated is reduced to boost the throughput. On the other hand, more protection is added when the channel condition becomes worse. Using this dynamically adjusted level of protection, the bit-error-rate (BER) is maintained at a constant target level over a range of channel condition.[1] It has been shown [14] that a significant gain in the average throughput can be achieved in these adaptive channel coding schemes. The proposed protocol, called SCAMA (synergistic channel adaptive multiple access), has been implemented and compared with DSA++ and DPRMA protocols. The results indicate that SCAMA can support a much larger user population with diverse traffic requirements. However, one may argue that the reported performance gain of our scheme is due to the variable-throughput physical layer, which is shown to offer a larger average transmission throughput compared with traditionally fixed-throughput physical layer. To illustrate that the performance gain is not just because of the higher average throughput of the adaptive physical layer, we also compare the proposed SCAMA with DTDMA/VR [9], which employs the same adaptive physical layer as ours (therefore enjoying the same average throughput) but does not take

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[1] When channel adaptive modulation and coding is employed, the penalty during poor channel condition is therefore a lower offered throughput instead of a higher error rate [12].

into account of CSI in the MAC-layer scheduling. Hence, DTDMA/VR is not a fully adaptive protocol.

This paper is organized as follows. In Section 2, the multiple access operations and characteristics of the proposed SCAMA protocol are described in detail. This is followed by Section 3, which delineates the physical layer of the proposed SCAMA protocol. Source models are discussed in Section 4. Experimental results and the respective interpretations are included in Section 5. Section 6 concludes the paper.

2. The SCAMA protocol

In this section, the functionality and characteristics of the proposed fully channel-adaptive MAC protocol are described. Based on D-TDMA framing, the proposed protocol also provides a convenient structure to accommodate different service requirements of CBR, VBR, and ABR effectively. Before introducing the proposed SCAMA protocol, existing MAC protocols for wireless ATM are first briefly reviewed.

2.1. Background

D-TDMA (dynamic TDMA) was first introduced for satellite communications [6] and has been proposed recently as a candidate MAC protocol for wireless ATM. There are many variations of D-TDMA-based MAC protocols. The DSA++ and DPRMA are well-known examples of D-TDMA-based MAC protocols. Despite that these protocols are different in many detailed aspects, such protocols can nevertheless be described by a common framework. Time on the channel is 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/UBR 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 (either voice or data slots). It often includes only very small of amount of information, namely the origin and the destination addresses, and is therefore usually much shorter than an information packet. The request subframe is usually operated using the slotted-ALOHA protocol.

A terminal generating a new stream of data cells transmits an appropriate request packet in one of the request slots of the next frame. If there are more than one packet transmitted in the same request slot, collision occurs and depending upon whether the capture effect [3] is considered, one or none of the requests will be correctly received (capture effect is considered in this study). At the end of each request slot, the successful or unsuccessful request will be identified and broadcast by the base station. Due to the short propagation delay in a FDD-based wireless ATM network, the mobile terminals can immediately know the request result. An unsuccessful user can retry in the next request slot. On the other hand, a successful user then transmits his/her information packet in the corresponding information slot in the current frame.

2.2. Frame structure

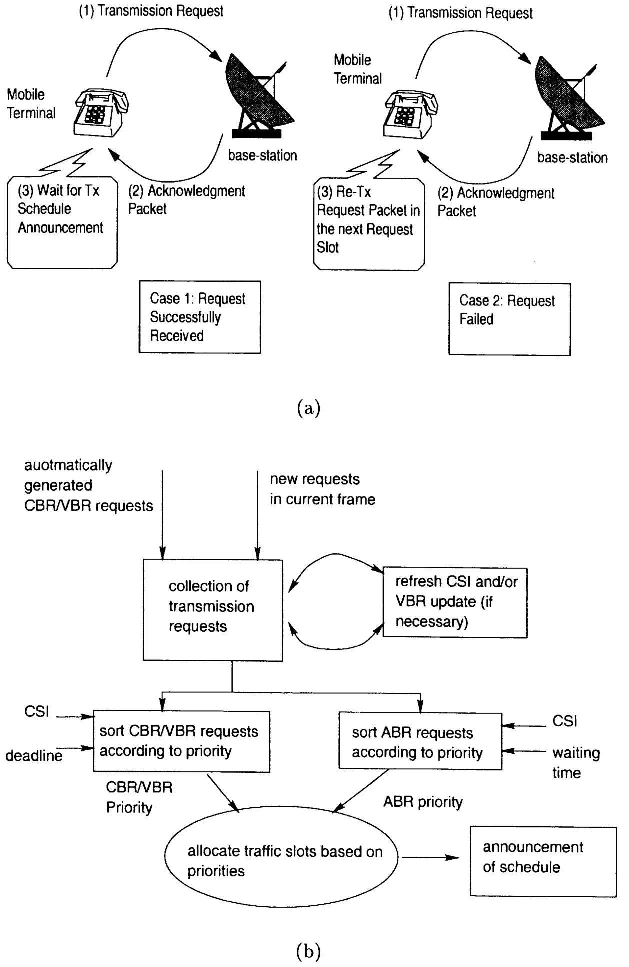
Fig. 2 shows the uplink and the downlink frame structure of the proposed MAC protocol. To incorporate the channel-adaptive feature of the proposed MAC protocol, the TDMA frames for the uplink and downlink are divided into subframes as follows.

In the uplink, a frame is divided into three subframes as illustrated in Fig. 2(a), namely the *request subframe*, the *traffic subframe*, and the *reporting subframe*. Specifically, there are N_{r} mini-slots in the request subframe for CBR, VBR, and ABR requests requests contention. Note that an ABR user is not allowed to make reservation in the sense that even if an ABR user is granted traffic slot(s) in the current frame, it has to contend again in the next frame for the remaining data cells. On the other hand, CBR and VBR users can reserve slots in succeeding frames. Specifically, when a CBR or VBR user successfully makes a transmission request in one of the N_{r} mini-slots, the user does not need to contend again in the next period and the request will be automatically generated in the MAC layer until the current burst ends. There are N_i information slots in the traffic subframe for the transmission of CBR, VBR, or ABR packets. Finally, there are N_b mini-slots in the reporting subframe. The functions of the three subframes will be elaborated in detail later in Section 2.3. The frame duration is 2.5 ms. Such a short frame duration has the advantage of shorter delay and is practicable in wideband systems [18].

A downlink FDD frame is similarly partitioned into four subframes, namely the *acknowledgment subframe*, the *polling subframe*, the *traffic subframe*, and the *announcement subframe*. The frame duration is also 2.5 ms and the number of slots in the subframes are given by N_{r}, N_b, N_i, and N_b, respectively. The functionality and operation of each subframe are described in Section 2.3. Note that in both uplink and downlink, variable throughput adaptive channel coding and modulation is applied to traffic slots only. For the mini-slots of the other subframes, fixed-rate trellis coded QPSK modulation is applied.

2.3. Protocol operations

The operation of the SCAMA protocol is divided into two phases, namely the *request phase* and *transmission 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, as illustrated in Fig. 2(a). 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



(a)

(b)

Fig. 3. Operations of the proposed channel-adaptive MAC protocol (SCAMA) for wireless ATM.

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 as illustrated in Fig. 3(a). 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 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). The time slot allocation algorithm is conceptually depicted in Fig. 3(b). 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 the sake of fairness, information slots should also be allocated to mobile terminals that are approaching the respective deadlines, despite the possibly worse channel states; otherwise, such information cells will be dropped by the mobiles.

2.4. *Priority function for slots allocation*

In general, a priority function for efficient slots allocation should satisfy the following objectives:

- give priority to requests with high CSI value;
- maintain priority (i.e. prevent priority inversion) between different classes (CBR, VBR or ABR), and
- maintain fairness (delay jitter) within each class.

The SCAMA protocol employs a general priority function, which could provide a flexible balance of the above conflicting goals. Furthermore, the slots allocation mechanism is also very flexible for incorporating other types of allocation algorithms such as deficit round robin, weighted fair queueing, and class-based queueing [21].

Specifically, the *priority metric* of the *i*th request, μ_i, is given by the following equation:

$$\mu_i = \begin{cases} g_{\mathrm{CBR}}(\mathrm{CSI}^{(i)}, T_{\mathrm{d}}^{(i)}) = f_\rho(\mathrm{CSI}^{(i)}) + \lambda_{\mathrm{CBR}}(T_{\mathrm{d}}^{(i)})^{-\beta_{\mathrm{CBR}}} + \Delta_{\mathrm{CBR}} & \text{for CBR request} \\ g_{\mathrm{VBR}}(\mathrm{CSI}^{(i)}, T_{\mathrm{d}}^{(i)}) = f_\rho(\mathrm{CSI}^{(i)}) + \lambda_{\mathrm{VBR}}(T_{d}^{(i)})^{-\beta_{\mathrm{VBR}}} + \Delta_{\mathrm{VBR}} & \text{for VBR request} \\ g_{\mathrm{ABR}}(\mathrm{CSI}^{(i)}, T_{\mathrm{w}}^{(i)}) = f_\rho(\mathrm{CSI}^{(i)}) + \lambda_{\mathrm{ABR}}(T_{\mathrm{w}}^{(i)})^{\beta_{\mathrm{ABR}}} & \text{for ABR request} \end{cases} \tag{1}$$

where $T_{\mathrm{d}}^{(i)}$, $T_{\mathrm{w}}^{(i)}$, λ_{CBR}, λ_{VBR}, λ_{ABR}, β_{CBR}, β_{VBR}, β_{ABR}, Δ_{CBR}, and Δ_{CBR}, Δ_{VBR}, are the deadline, the waiting time, the *forgetting factors* of the CBR, VBR and ABR requests, as well as the *priority offsets* assigned to the CBR, VBR, or ABR users, respectively. From Eq. (1), the first term is aimed to enforce that a higher priority for requests with a higher throughput. The second term is to maintain fairness[2] within each of the service classes. Finally, the last term is responsible for maintaining priority between different classes. As will be demonstrated in Section 5, the balance between the three goals could be easily adjusted by tuning λ and Δ.

Thus, in the allocation phase, traffic slots are allocated to service requests according to the sorted priority metrics. If there are not sufficient traffic slots to service all requests,

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[2] The second term will be large for requests with a urgent deadline or long waiting time.

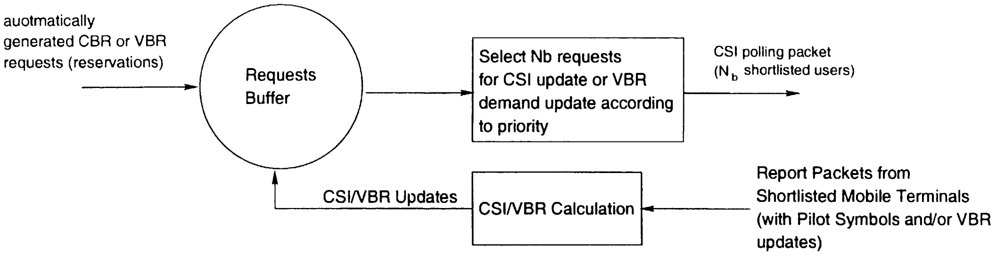


Fig. 4. Information (CSI or VBR demands) updating mechanism for automatically generated requests.

remaining requests are discarded. After the request phase, the results of traffic slot allocation will be broadcast in the *announcement subframe* of the downlink frame. The announcement packet contains the traffic slot allocation schedule as well as the transmission mode as illustrated in Fig. 2(b). Mobile terminals will then start to transmit information packets on the allocated traffic slot(s).

2.5. Handling heterogeneous user requirements

The SCAMA protocol is reservation based for CBR and VBR users only. As mentioned earlier, for a ABR user, even if traffic slots have been assigned for its successfully acknowledged request, the allocation is meant only for the current frame and the ABR user has to initiate another request for any remaining data cells. By contrast, for a CBR or VBR user, when traffic slots have been assigned for its successfully acknowledged request, additional requests will be *automatically generated* by the base-station (hence, reservation) periodically at 20 ms (i.e. taking voice as an example CBR source) and 40 ms (i.e. taking video as an example VBR source) time intervals for CBR and VBR, respectively. Thus, the CBR or VBR user does not need to contend for request mini-slots anymore in the current talkspurt. By avoiding unnecessary requests, the advantage of this reservation strategy is the reduction of the contention collisions in the request phase. For a CBR user, the number of cells generated per CBR period is constant and hence, this basic reservation scheme works fine. However, for a VBR user, the number of cells generated per VBR period is a random variable and hence, this information needs to be updated per VBR period in order to make proper reservation for VBR. The mechanism for VBR updating is illustrated in the following section.

2.6. CSI determination

On the other hand, a critical component in the proposed SCAMA MAC protocol is the determination of the current CSI for each user. As will be detailed below, it is assumed that the coherence time for short-term fading is around 20 ms as illustrated in Section 3 while the frame duration is only 2.5 ms. Thus, the CSI remains approximately constant for at least two frames. For a new request, known pilot symbols are embedded in the request packets so that the current CSI can be estimated at the base station and this estimated CSI is valid for the next few frame duration. However, for those automatically generated CBR or VBR request, the estimated CSI value obtained previously during a past request phase may be obsolete and thus, a mechanism is needed to obtain update the CSI.

Both the VBR reservation and the CSI update relies on a special updating procedure, which is illustrated in Fig. 4. At the beginning of each frame, the base-station short-lists N_b automatically generated requests according to their previous priorities. A *polling packet* is then broadcast to the mobile terminals in the *polling subframe*. The CSI polling packet contains the mobile terminal IDs that are short-listed by the base-station. The structure of the polling packet is shown in Fig. 2(b). Mobile terminals listed in the polling packet respond at the appropriate reporting mini-slot according to the order specified in the polling packet. If the short-listed request is of CBR-type with CSI value expired, the mobile station will transmit pilot symbols in the reporting mini-slot. Otherwise, the mobile station will transmit a VBR demand update packet as shown in Fig. 2(a). The VBR demand update packet contains the number of VBR cells generated in the current frame as well as pilot symbols for CSI updating.

Thus, the base station could update the VBR reservation requests as well as the CSI values (which are valid for at least two consecutive frames). The estimated CSI value is used to determine the transmission mode in the physical layer as well as to determine the priority of the request in the MAC layer. With the above considerations, the SCAMA protocol is outlined below in pseudocode format.

```
loop
    contention phase {requests are acknowledged but no slot is assigned}
    CSI of each request is recorded
    arrange the new requests as a request queue
    sort the request queue according to the request priority
    assign information slots according to the request queue order
    remaining unassigned requests are discarded
end loop
```

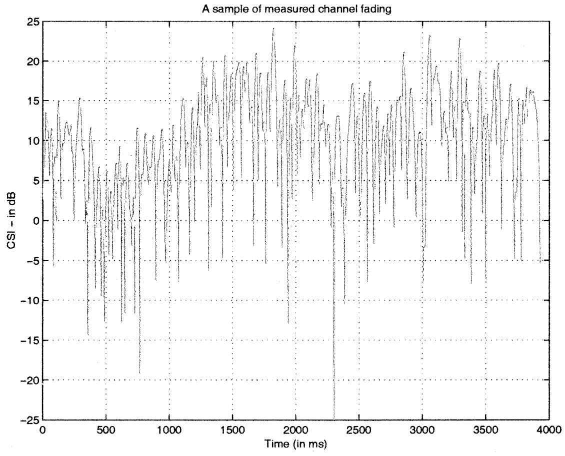


Fig. 5. A sample of channel fading with microscopic fading superimposed on macroscopic shadowing.

2.7. *Queue for backlog requests*

The SCAMA protocol described above can incorporate a *backlog request queue*, which stores at the base-station the previous requests that survive the contention but are not allocated information slots. Such a backlog request queue can further alleviate the capacity loss due to requests contention. However, because the CSI values of the queued requests need to be updated, additional overheads are incurred for CSI reporting of the queued requests. Due to space limitations, the case of using a backlog request queue is not considered in the present paper and the results of SCAMA with backlog request queue are discussed elsewhere [13]. In this study, a variant of SCAMA without the backlog request queue is examined. The requests, which are not allocated information time slots, are simply dropped. Such users will therefore make requests again, as governed by the permission probabilities. The advantage of this no-queue SCAMA is that there is no need to occupy the uplink and downlink bandwidth for updating CSI values of queued requests.

3. The channel-adaptive physical layer

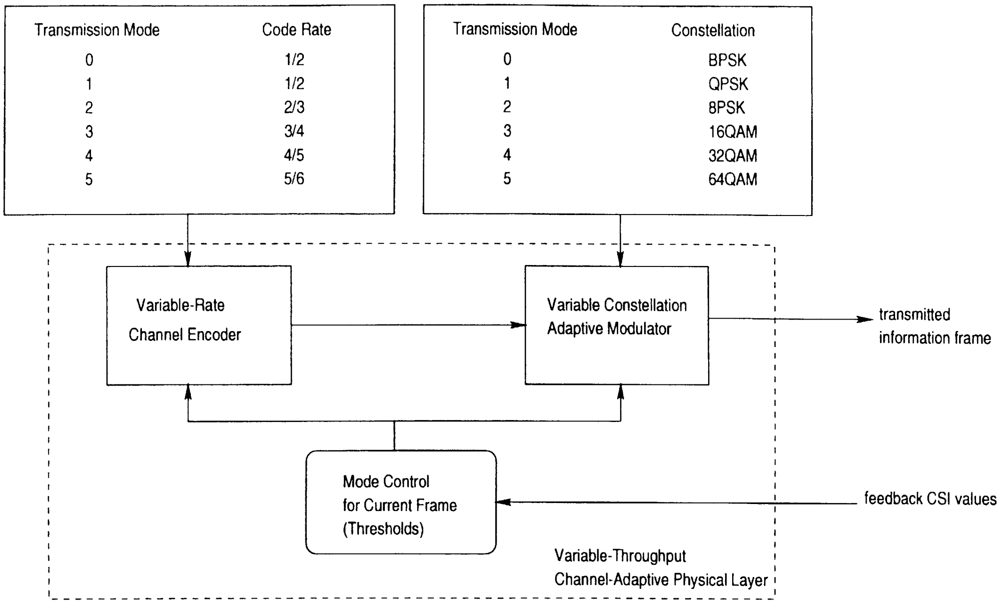
3.1. *Wireless channel model*

The wireless communication environment considered in this paper is the reverse-link situation of a wireless system where a number of mobile terminals contend to transmit ATM cells to an ATM server. The wireless link between a mobile ATM terminal and the ATM server is characterized by two components, namely the *microscopic fading* component and the *macroscopic shadowing* component. Microscopic fading is caused by the superposition of multipath components and is therefore fluctuating in a fast manner (on the order of a few ms). Macroscopic shadowing is caused by terrain configuration or obstacles and is fluctuating in a relatively slow manner (on the order of 1–2 s). To illustrate, a sample of measured fading signal is shown in Fig. 5.

Let $c(t)$ be the combined channel fading, which is given by:

$$c(t) = c_l(t)c_s(t)$$

where $c_l(t)$ and $c_s(t)$ are the long-term macroscopic and short-term microscopic fading components, respectively. Both $c_s(t)$ and $c_l(t)$ are random processes with coherent time on the order of a few milli-seconds and seconds, respectively.



Transmission Mode	Code Rate
0	1/2
1	1/2
2	2/3
3	3/4
4	4/5
5	5/6

Transmission Mode	Constellation
0	BPSK
1	QPSK
2	8PSK
3	16QAM
4	32QAM
5	64QAM

Fig. 6. A conceptual block diagram of the variable throughout channel adaptive physical layer.

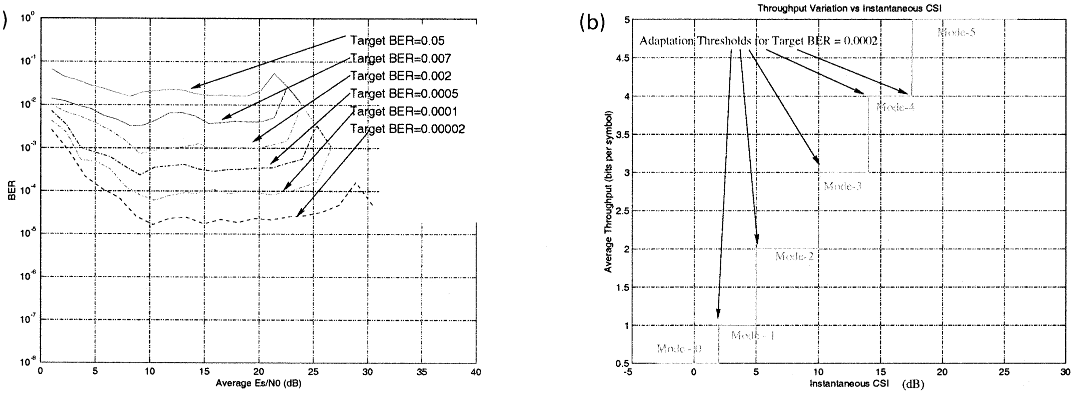


Fig. 7. BER and throughput of ABICM scheme.

3.1.1. Short-term microscopic fading

Without loss of generality, it is assumed $\mathscr{E}[c_s^2(t)] = 1$ where $\mathscr{E}[\ ]$ denotes the expected value of a random variable. The probability distribution of $c_s(t)$ follows the Rayleigh distribution which is given by:

$$f_{c_s}(c_s) = c_s \exp\left(-\frac{c_s^2}{2}\right)$$

In this paper, it is assumed that the maximum mobile speed is 40 km/h and hence, the Doppler spread [20], $f_d \approx 50$ Hz. It follows that, the *coherent time* T_c is approximately given by:

$$T_c \approx \frac{1}{f_d} \tag{2}$$

which is about 20 ms.

3.1.2. Long-term macroscopic shadowing

The long-term fading component $c_l(t)$ is also referred to as the *local mean* [20], which, as shown by field test measurement, obeys the *log-normal* distribution, $f_{c_l}(c_l)$. That is,

$$f_{c_l}(c_l) = \frac{4.34}{\sqrt{2\pi}\sigma_l c_l} \exp\left(-\frac{(c_l(\mathrm{dB}) - m_l)^2}{2\sigma_l^2}\right)$$

where m_l, σ_l are the mean (in dB) and the variance of the log-normal distribution, i.e. $c_l(\mathrm{dB}) = 20\log(c_l)$. Since $c_l(t)$ is caused by terrain configuration and obstacles, the random process fluctuates over a much longer time scale. Again, from field test results, the order of time span for $c_l(t)$ is about 1 s. Since mobile terminals are scattered geographically across the cell and are moving independently of each other, it is assumed that the channel fading experienced by each mobile terminal is independent of each other.

3.2. Variable throughput channel coding

Redundancy is incorporated to the information packet for error protection. To exploit the time-varying nature of the wireless channel, a variable rate channel-adaptive physical layer is employed as illustrated in Fig. 6(a). Channel state information (CSI) $c(t)$, which is estimated[3] at the receiver, is fed back to the transmitter via a low-capacity *feedback channel*. Based on the CSI, the level of redundancy and the modulation constellation applied to the information cells are adjusted accordingly by choosing a suitable transmission mode.[4] Thus, the instantaneous throughput is varied according to the instantaneous channel state. In this study, a 6-mode variable rate adaptive bit-interleaved trellis coded modulation scheme (ABICM) is employed [12]. Transmission modes with *normalized throughput*[5] varying from 1/2 to 5 are available depending on the channel condition. For real-time sources such as CBR or VBR, the physical layer employs a variable throughput forward error correction (FEC) code. For a non-real-time source such as ABR, the physical layer employs a variable throughput error correction code embedded with error detection and retransmission.

Information cells per user are transmitted in the assigned traffic slots of a TDMA frame. Since the coherence time of short-term fading is around 20 ms, the CSI remains approximately constant within a traffic slot duration. Hence, all the transmitted symbols of the traffic slot (per user) share the same transmission mode, which is determined by the current CSI level. Specifically, transmission mode q is chosen if the feedback CSI, $\hat{c}$, falls within the *adaptation thresholds*, (ζ_{q-1}, ζ_q). Here, the operation and the performance of the ABICM scheme is determined by the set of adaptation thresholds $\{\zeta_0, \zeta_1, \ldots\}$. Furthermore, the ABICM scheme is operated in the *constant BER* mode [12]. That is, the adaptation thresholds are set optimally to maintain a target transmission error level over a range of CSI values. When the channel condition is good, a higher mode could be used

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[3] In this paper, it is assumed that CSI is estimated by the pilot-symbol approach [12].

[4] Transmission mode refers to the combination of channel encoding rate and modulation constellation level.

[5] Normalized throughput refers to the number of information bits carried per modulation symbol.

Table 1
Simulation parameters

Parameter	Value
N_r	40
N_I	38
N_b	20
t_t	1000 ms
t_s	1350 ms
p_c	0.3
p_v	0.3
p_a	0.2
Channel bandwidth	1.36 MHz
CBR (voice) data rate	8 kbps
VBR (video) data rate	128 kpbs
ABR data rate	16 kbps
Number of simulated frames	2×10^6

and the system enjoys a higher throughput. On the other hand, when the channel condition is bad, a lower mode is used to maintain the target error level at the expense of a lower transmission throughput. Note that when the channel state is very bad, the adaptation range of the ABICM scheme can be exceeded, making it impossible to maintain the targeted BER level. The concept of constant BER operation is illustrated in Fig. 7(a).

Given the above considerations about the channel state, the instantaneous throughput offered to the MAC layer, ρ, is also variable and is therefore a function of the CSI, $c(t)$, and the target BER, P_b, denoted by $\rho = f_\rho(c(t), P_b)$. Fig. 7(b) illustrates the variation of ρ with respect to the CSI.

4. Source models

The wireless ATM system considered in this paper is aimed to support integrated CBR, VBR, and ABR services. As such, it is assumed 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 Ref. [8]) in order to have acceptable quality of service for CBR and VBR users. The source and contention models are summarized below:

- *CBR source model*: Voice is used 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 Ref. [8], $t_t = 1$, and $t_s = 1.35$). It is assumed that 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 [8].
- *VBR source model*: Video teleconference is used as an example VBR source. In the model used [11], the number of cells per VBR period (i.e. 40 ms 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:

$$P = \rho I + (1 + \rho)Q \tag{3}$$

  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 $(f_0, \ldots, f_K, F_K)$, 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 [11].
- *ABR source model*: The arrival time of data generated by a ABR data terminal is assumed to be exponentially distributed with mean equal to 1 s. 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 it is assumed 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.

It is also interesting to investigate the performance of the proposed SCAMA protocol under situations with capture. Thus, the capture process is also implemented. Specifically, suppose there are k requests, with signal power denoted by $P_1, P_2, \ldots, P_k$, contending for a request mini-slot. A request j can be captured if [3]:

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

where γ is the SNR threshold.

5. Performance results

In this section, the performance results of the proposed protocol and the respective interpretations are presented. In the simulation study, it is assumed that 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 1 summarizes the parameters used.

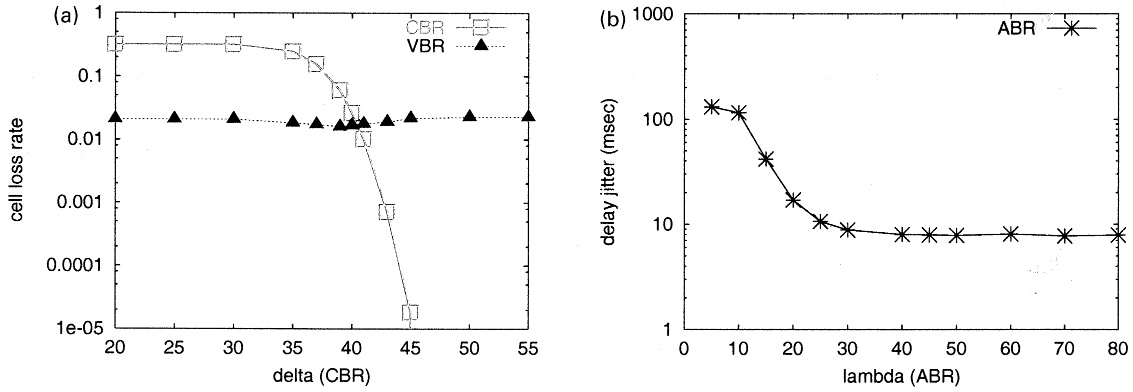

Fig. 8. Effects of Δ and λ.

5.1. Priority control between traffic classes

As described in Section 2.4, the priority function employed in the proposed protocol is very flexible in adjusting priority between different traffic classes. This is illustrated in Fig. 8(a) where the variation of the cell loss rates of CBR and VBR users (with a particular combination of Δ_{CBR} and Δ_{VBR}) against Δ_{CBR} (Δ_{VBR} is fixed at 40) are shown. As can be seen, the cell loss rate of CBR improves while that of VBR increases as Δ_{CBR} is increased. This indicates that priority could be shifted to the CBR users by increasing Δ_{CBR}. This robustness of the priority function can be employed to dynamically adjust the relative service quality of different user classes depending on the traffic condition. For example, if it is noted that the current number of admitted VBR users is small, say less than 25, then the value of Δ_{CBR} can be increased to further improve the service quality of the CBR users without significantly degrading the service quality of the VBR users. This can be done similarly for VBR users if needed.

5.2. Priority control within a traffic class

The proposed priority function is also very flexible in adjusting the priority and hence the fairness, within each class. As mentioned in Section 2.4, although it is efficient to give a higher priority to a request with a high CSI value, it would also be unfair to those requests with inferior CSI values because such requests may have to wait for a long time in the mobile's buffer to get service. Thus, there is a design trade-off between system efficiency and fairness. Depending upon the desired service conditions, fairness could be promoted by adjusting the priority within a traffic class, which could be easily done by changing λ in Eq. (1). As an example, the delay jitter of the ABR users is measured, with background CBR and VBR traffic, against λ, which is shown in Fig. 8(b). Clearly, by choosing an appropriate value of λ, the delay jitter of ABR users can be easily controlled to fall within the desired range.

5.3. Comparison with other MAC protocols

It is interesting to compare the MAC performance of the proposed SCAMA protocol with well-known ATM MAC protocols such as DSA++ [17] and DPRMA [5]. However, in order to illustrate that the performance improvement of the proposed scheme over other protocols is *not* entirely due to the variable-throughput physical layer, which has been shown to offer a larger average throughput compared with traditional fixed-throughput physical layers [2], one additional MAC protocol, namely the DTDMA/VR [9], employing the same variable-throughput physical layer, is also included in the comparison. The characteristics of the DSA++ and DPRMA protocols are summarized earlier in Section 1. For completeness, the characteristics of the DTDMA/VR protocol is briefly summarized as follows. In the DTDMA/VR [9] protocol, the MAC layer assigns information slots to the users on a first-come-first-serve basis. 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. All the three baseline protocols incorporate a piggybacking mechanism for VBR users to update the respective traffic demands. All of the schemes are compared based on the same bandwidth, BER level and the average transmitted power. The reader is referred to the respective references for further details about these three protocols.

5.3.1. 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 deadline.[6] Such discarding constitutes the cell dropping at the

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[6] Normalized throughput refers to the number of information bits carried per modulation symbol.

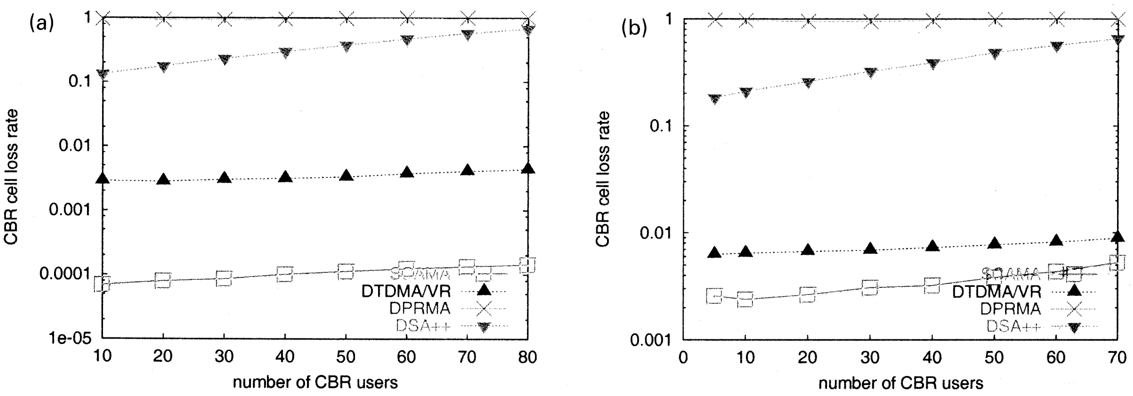

Fig. 9. Performance of the protocols for CBR users.

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:

$$P_{\text{loss}} = \frac{N_{\text{tx}} - N_{\text{rv}}}{N_{tx}} \quad (4)$$

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

Fig. 9 shows the cell loss rate performance of the proposed SCAMA protocol as well as the other three previous protocols. In the set of experiments shown in Fig. 9(a), the number of ABR users is fixed to be 25 and that of VBR users to be 20 also. As can be seen, the DPRMA and DSA++ protocols perform much worse compared with the DTDMA/VR and SCAMA protocols. Indeed, the former two protocols achieve a cell loss rate, which is higher than the 1% tolerance threshold for a voice source [8], while the latter two offer more than one order of magnitude lower cell loss rate. 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 [5]. The relatively inferior performance of the DPRMA protocol can be explained by the fact that the contention in the protocol becomes very heavy even for a few tens of users in the system, no matter what traffic classes these users belong to. The main drawback in the DPRMA protocol is that information slots, instead of mini-slots, are directly used for requests contention. DSA++ performs much better than DPRMA for small number of CBR users. However, the DSA++ protocol also becomes highly congested when the number of CBR users is large (e.g. 60). In addition, in the DSA++ protocol, a higher priority is given to a request with more cells waiting to be sent. Thus, a moderate number of VBR users can saturate the system. On the other hand, the SCAMA protocol remarkably outperforms the DTDMA/VR protocol due to the judicious allocation algorithm used in the SCAMA. The results for 25 VBR users shown in Fig. 9(b) concur with these observations.

5.3.2. 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 a isochronous source, cells have deadlines such that missing the transmission deadlines render the cells useless. Thus, the performance of the protocols is

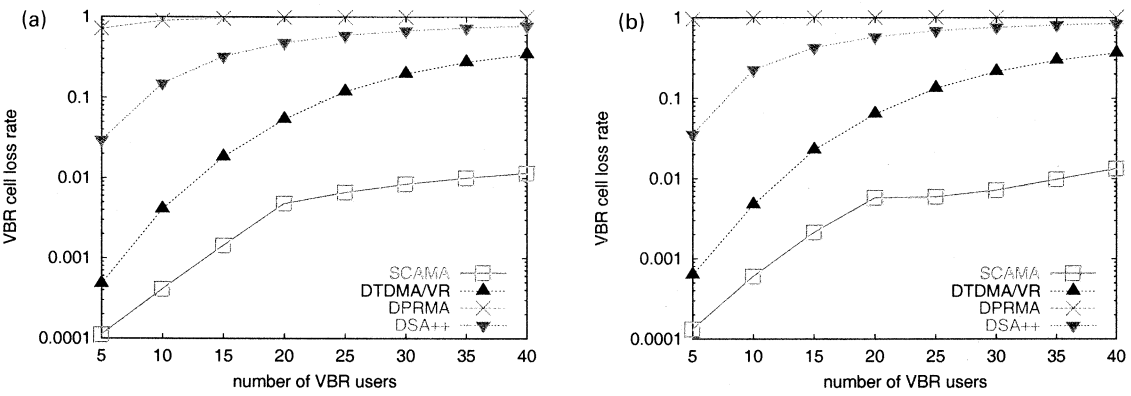

Fig. 10. Performance of the protocols for VBR users.

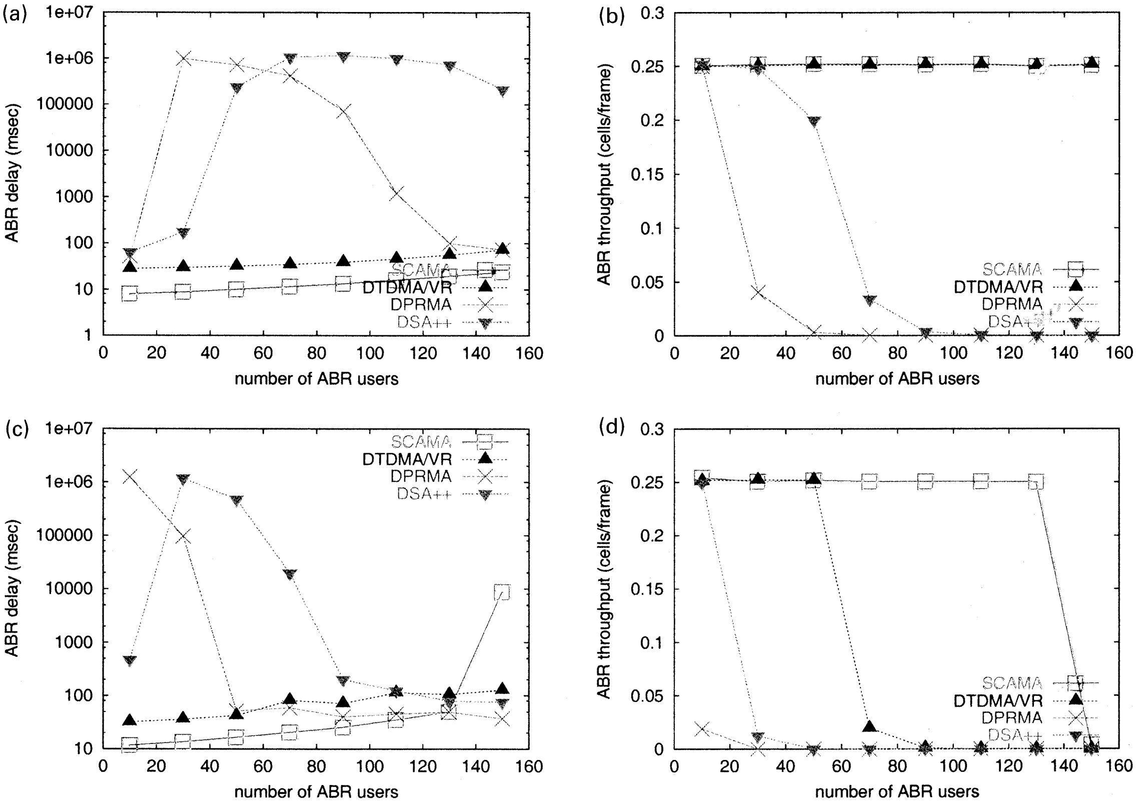

Fig. 11. Performance of the protocols for ABR users.

also evaluated using the cell loss rate for VBR users. Fig. 10 depicts the VBR cell loss rate performance of the four protocols. As can be seen, similar to CBR performance, the DSA++ and DPRMA protocols also perform quite poorly for VBR users in that the cell loss rate is much higher than the 1% threshold even for 10 VBR users. Here, the major reason for the poor performance of these two protocols is again due to the contention overload problem. Finally, it is evident that the proposed 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.

5.3.3. ABR performance

ABR cells are delay insensitive and as such, these cells 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 $\bar{D}_{\mathrm{d}}$ is defined as the average time that a cell spends waiting in the transmitter buffer until the beginning of the successful transmission. Fig. 11 illustrates the performance of data terminal in terms of $\bar{\rho}$ and $\bar{D}_{\mathrm{d}}$, respectively. 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 proposed 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.

5.4. Interpretations

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

First, a CBR terminal may experience a deep fading for a long time when it is affected by shadowing. In the other three 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.

Secondly, selection diversity is implicitly incorporated in the SCAMA protocol. Through the priority-based assignment 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, the transmissions are deferred until when the CSI improves or the deadlines are approaching. By contrast, in the DTDMA/VR protocol, 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 the 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 (DSA++ and DPRMA) or those even without explicit prioritization (DTDMA/VR), 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 proposed scheme 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.

5.5. Applicability in other wireless systems

It is tempting to consider the applicability and performance of the SCAMA protocol under other more modern wireless communication systems such as UMTS (Universal Mobile Telecommunication System) and IMT2000 [7,15,16]. Being an ITU standard, UMTS is a versatile system that can provide various mobile services to a wide range of global mobile communication standards [4,19]. A critical novelty of the UMTS is a mixed hierarchical cell layout — a number of large macrocells are overlaid on micro and picocells. Such a hierarchical arrangement can support a mixed range of traffic with different mobility characteristics. For example, a swiftly moving end user can be handled by a macrocell so that fewer handoffs are needed. The SCAMA protocol, which is designed to work under an environment that allows fast feedback — for updating CSI and notification of information slots contention results, can be applied at the picocell level. However, the detailed performance of SCAMA under a picocell of UMTS is yet to be investigated.

6. Conclusions

A new channel-adaptive MAC protocol for wireless ATM systems is presented. The proposed protocol, called SCAMA, employs a judicious prioritization and scheduling mechanism, which takes into account all the critical performance parameters such as channel condition, urgency, and throughput. In particular, the prioritization is robust and flexible in that it can be easily adapted to suit the needs of a certain class of users (e.g. the CBR users). Simulation results indicate that the performance of the SCAMA protocol is superior to three state-of-the-art wireless ATM MAC protocols. The performance of the SCAMA protocol under more modern wireless communication systems such as UMTS and IMT2000 is currently being investigated.

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References

[1] A. Acampora, Wireless ATM: a perspective on issues and prospects, IEEE Personal Communications August (1996) 8–17.

[2] S.M. Alamouti, S. Kallel, Adaptive Trellis-coded multiple-phase-shift keying for Rayleigh fading channels, IEEE Transactions on Communications 42 (6) (1994) 2305–2314.

[3] J.C. Ambak, W. van Blitterswijk, Capacity of slotted ALOHA in Raleigh fading channels, IEEE Journal on Selected Areas in Communications SAC-5 (2) (1987) 261–268.

[4] E. Dahlman, B. Gudmundson, M. Nilsson, A. Skold, UMTS/IMT-2000 based on wideband CDMA, IEEE Communications Magazine 36 (9) (1998) 70–80.

[5] D.A. Dyson, Z.J. Haas, A dynamic packet reservation multiple access scheme for wireless ATM, Mobile Networks and Applications 4 (1999) 87–99.

[6] G. Falk, J.S. Groff, W.C. Milliken, M. Nodine, S. Blumenthal, Edmond, Integration of voice and data in the wideband packet satellite network, IEEE Journal on Selected Areas in Communications SAC-1 (6) (1983) 1076–1083.

[7] M. Gallagher, W. Webb, UMTS: the next generation of mobile radio, IEE Review 45 (2) (1999) 59–63.

[8] J. Gruber, L. Strawczynski, Subjective effects of variable delay and

speech clipping in dynamically managed voice systems, IEEE Transactions on Communications COM-33 (8) (1985) 801–808.

[9] M. Kawagishi, S. Sampei, N. Morinaga, A novel reservation TDMA-based multiple access scheme using adaptive modulation for multimedia wireless communication systems, Proceedings of VTC'98, 1998, pp. 112–116.

[10] Q. Kubbar, H.T. Mouftah, Multiple access control protocols for wireless ATM: problems definition and design objectives, IEEE Communications Magazine November (1997) 93–99.

[11] T.V. Lakshman, A. Ortega, A.R. Reibman, VBR radio: tradeoffs and potentials, Proceedings of the IEEE 86 (5) (1998) 952–973.

[12] V.K.N. Lau, Performance of variable rate bit-interleaved coding for high bandwidth efficiency, Proceedings of VTC'2000, Tokyo, May 2000, accepted for publication and to appear.

[13] V.K.N. Lau, Y.-K. Kwok, On channel adaptive multiple access control with queued transmission requests for wireless ATM, Technical Report, HKU EEE Department, December 1999.

[14] V.K.N. Lau, S.V. Maric, Variable rate adaptive modulation for DS-CDMA, IEEE Transactions on Communications 47 (4) (1999) 577–589.

[15] T. Ojanpera, R. Prasad, An overview of air interface multiple access for IMT-2000/UMTS, IEEE Communications Magazine 36 (9) (1998) 82–86 (also pp. 91–95).

[16] D. O'Mahony, UMTS: the fusion of fixed and mobile networking, IEEE Internet Computing 2 (1) (1998) 49–56.

[17] D. Petras, A. Krämling, MAC protocol with polling and fast collision resolution for an ATM air interface, Proceedings of the IEEE ATM Workshop, August 1996.

[18] A. Urie, M. Streeton, C. Mourot, An advanced TDMA mobile access system for UMTS, Proceedings of the IEEE, PIMRC'94, 1994.

[19] G. Vincent, Mobilising the Net, IEE Review 45 (6) (1999) 241–245.

[20] M.D. Yocoub, Foundations of Mobile Radio Engineering, McGraw Hill, New York, 1986.

[21] H. Zhang, Service disciplines for guaranteed performance service in packet-switching networks, Proceedings of the IEEE 83 (10) (1995) 1374–1396.