A Survey of MAC Protocols Proposed for Wireless ATM

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Abstract

Wireless ATM (W-ATM) networks have been studied extensively in recent years. Extension of ATM network services to the wireless environment faces many interesting problems. The original ATM network was designed for high-speed, noiseless, reliable channels. None of these characteristics are applicable to the wireless channel. One of the most critical aspects of a W-ATM network is the medium access control (MAC) protocol used by mobile terminals (MTs) to request service from the base station (BS), which has to consider the quality of service (QoS) of the specific application. In this article the authors analyze some recently proposed MAC protocols, particularly those for TDMA systems, and discuss their advantages and disadvantages.

Asynchronous transfer mode (ATM) has been adopted as the switching and transport infrastructure for the future broadband integrated services digital network (B-ISDN). The extension of broadband services to the wireless environment is being driven mainly by the proliferation of multimedia portable computers, personal digital assistants, and personal information assistants [1]. Although there are various competing technologies that may provide these services, such as third-generation cellular networks (e.g., personal communications services, PCS) and wireless local area networks (WLANs), wireless ATM (W-ATM) has the advantage of offering end-to-end multimedia capabilities with guaranteed quality of service (QoS). Furthermore, ATM can handle both packet mode and synchronous services.

Several issues have to be resolved in order to arrive at a W-ATM network; one of the most important is the MAC protocol, which is tightly related to the actual physical layer (PHY) adopted.

Generally, the radio link presents problems such as noise, interference, and limited channel bandwidth (BW). The interference depends greatly on the cell size covered by the base station (BS), and the mobility of the mobile terminals (MTs).

The basic wireless architecture considered in this article is the classical cell,[1] with a BS serving a finite set of MTs by means of a shared radio channel. The BS is connected to an ATM switch by means of cable or fiber optics so that it can access the wired ATM network.

In general, the proposals for the PHY of the W-ATM network can be divided in two broad types:

- Spread spectrum (SS) techniques, where all MTs in a cell transmit at will using the whole spectrum of the channel simultaneously. SS techniques may use frequency hopping or direct sequence; the natural access technique for SS is code-division multiple access (CDMA).
- Time-division multiplex (TDM), where MTs transmit at specific times using the total available radio frequency (RF) spectrum. The access technique in this case is time-division multiple access (TDMA).

Even though SS techniques have been shown to be very robust to interference and frequency reuse [2], and are very appropriate for the digital cellular network, they have a severe disadvantage at high bit rates. In the case of direct sequence SS [3] the robustness is directly proportional to the spreading gain (SG), and the number of MTs that can communicate simultaneously with the BS increases with the SG. However, an increase in SG implies the need for more BW.

For example, an SG of 100 at a bit rate of 100 Mb/s would require at least 10 GHz of BW (assuming a modulation scheme of 1 b/Hz); this makes CDMA unattractive for broadband W-ATM, at least with currently available radio technologies. On the other hand, if SS is used the MAC protocol is greatly simplified, since there is no contention involved (all terminals in a cell may transmit simultaneously). An example of a W-ATM network prototype that uses frequency-hopping SS is the SWAN network described by Agrawal *et al.* in [4]. Since there is no need to handle access contention, the MAC protocol focuses mainly on higher-level functions such as

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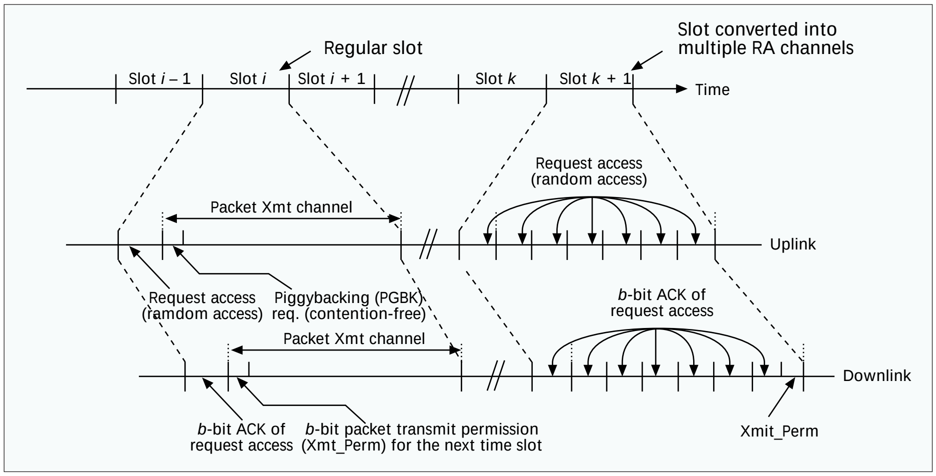
[1] *In this article, we use the term "cell" to refer to the area served by a BS.*



■ Figure 1. *DQRUMA timing diagram.*

packet scheduling, admission control, and handoff mechanism.

Since we are interested in future broadband ATM networks, which may offer services up to 150 Mb/s (when technology advances allow it), we will focus on the analysis of proposed TDMA techniques. Actually, some research projects are already considering bit rates of 20 Mb/s [5] and even 150 Mb/s [6] using TDMA.

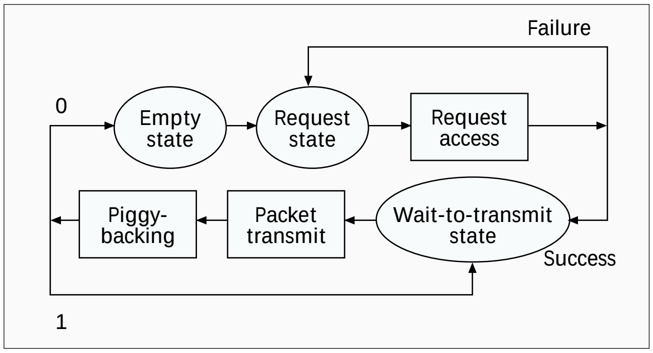
Most TDMA proposals use the random access technique called slotted ALOHA (or a variant of this protocol) for the dialup process and reservation of slots for transmission from the MTs to the BS. This transmission is done in what is known as an *uplink* (UL) channel, usually in contention among the MTs. Consequently, most proposals do not analyze the communication from the BS to the MTs, called *downlink* (DL), which is realized by a TDM technique, since the BS has total control (except for the noise) of the channel through a scheduler.

Within the TDMA proposals, we will make a further distinction according to the number of carrier frequencies used between the BS and the MTs: frequency-division duplex (FDD), which uses two frequencies, and time-division duplex (TDD), which uses only one frequency carrier.

The organization of this article is as follows. In the second section we describe MAC protocols that use the FDD method, while protocols that use the TDD method are presented in the third section. After the description of each protocol we highlight its advantages and disadvantages. In the fourth section we present a comparison of the main characteristics of each protocol, and end the article with some conclusions.

FDD-Based MAC Proposals

The idea behind FDD is to have two channels per BS coverage area, one for the UL and the other for the DL. Usually, the UL is used by the MTs for sending request and information packets, according to some reservation and contention algorithm, while the DL is used by the BS in a scheduled mode, for sending acknowledgments (ACKs) and information packets. Due to the availability of these two channels, it is possible to have an almost immediate (depending on distance and bit rate, as discussed later) feedback from the BS in order to know (at the MT) if a request was successful or if a collision occurred.



■ Figure 2. *DQRUMA channel model.*

The MAC protocol proposals (listed according to publication date) considered in this section are: DQRUMA, PRMA/DA, DSA++, and DTDMA/PR.

Distributed Queuing Request Update Multiple Access (DQRUMA)

The DQRUMA protocol was proposed by Karol *et al.* [7].

Description of the Protocol — This protocol considers a time-slotted system with no frame reference, where the request access (RA) and packet transmission (Xmt) channels are formed on a slot-by-slot basis. The UL stream is divided in a series of minislots used for requesting access (RA channel), each one followed by a slot for packet transmission (Xmt channel). If needed, the BS can convert a Xmt channel into *M* RA channels, where *M* depends on the round-trip propagation delay for a transmission from a remote MT. Figure 1 shows the basic timing structure of the DQRUMA protocol.

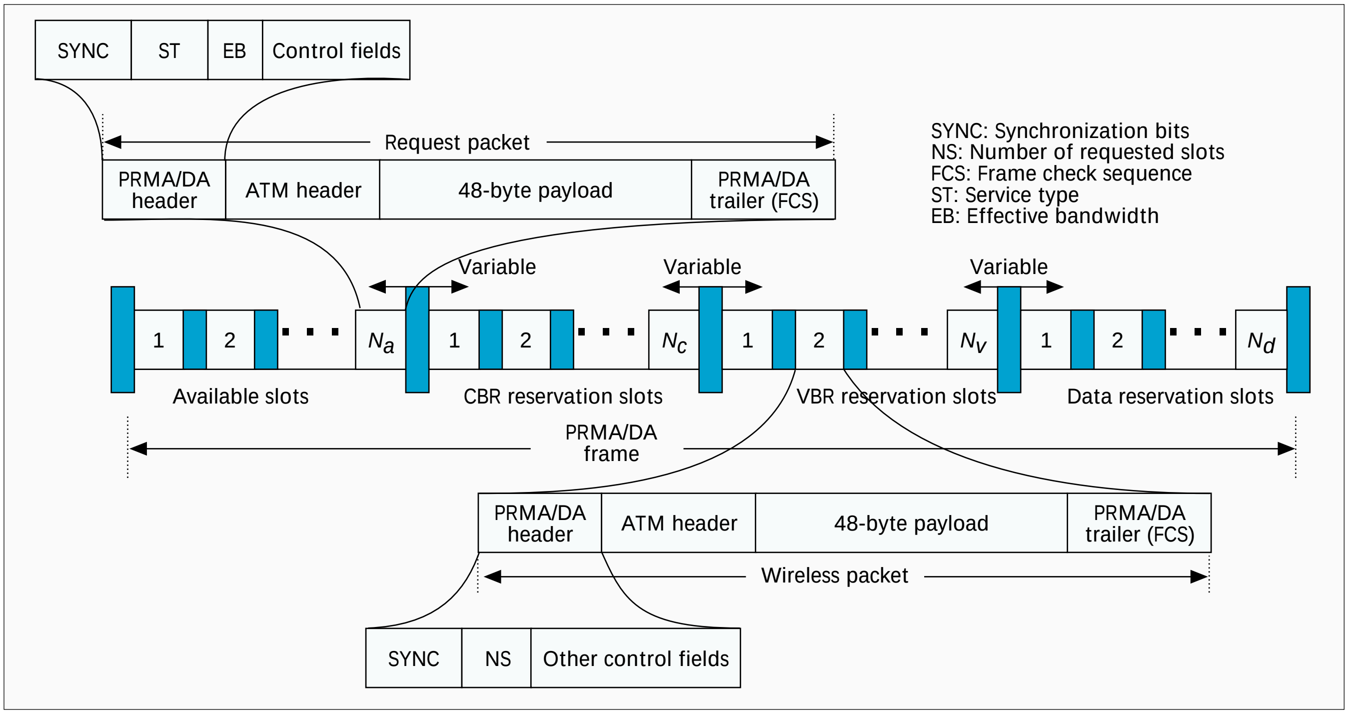
The downlink (DL) channel consists of a series of minislots for acknowledgment of request accesses, each followed by a slot for packet transmission. Whenever the BS receives a successful request from an MT, it immediately sends the corresponding ACK in the appropriate DL minislot.

The channel model considers the MTs to be in one of three states: "empty," "request," and "wait to transmit." When a mobile registers with a BS, because of a call setup or handoff, it is assigned a local ID, called a "*b-bit access ID*." As soon as a packet arrives at a MT with its buffer empty, the mobile sends a Xmt_Req (including its b-bit access ID) to the BS using the UL request channel (possibly in contention with other MTs) and changes its state to "request."

After receiving the Xmt_Req from a MT, the BS updates the corresponding entry in a request table (RT), which has an entry for each of the *N* mobiles contained in the cell, and sends an ACK to the MT. Each entry in the RT contains the b-bit access ID and information about whether the MT has more packets to transmit.

After the reception of the positive ACK to its Xmt_Req, the MT switches to the wait-to-transmit state and keeps listening to the DL Xmt_Perm channel, waiting for permission to transmit from the BS.

When the BS decides to allow transmission by a particular MT from the RT (according to the current traffic load and a round-robin policy), it sends a transmit permission (Xmt_Perm) through the DL Xmt_Perm channel. The corresponding MT, after detecting its own b-bit ID, transmits a packet in the next slot and switches to either the empty state



■ Figure 3. *PRMA/DA frame format.*

(if it has no more packets in the queue) or the wait-to-transmit state (if it has more packets). Figure 2 shows the channel model for the MT.

Each time an MT transmits an ATM packet, it includes a piggyback message in case it has more packets to transmit. In this way, the MT does not have to make a reservation while its buffer is not empty. This simplifies the protocol and saves BW.

The authors analyze two possible methods for random access to the RA channel:

- Dynamic Access Channel Slotted ALOHA with Harmonic Backoff algorithm (attempt probabilities: 1, 1/2, 1/3, 1/4,...)
- Dynamic Access Channel Binary Stack algorithm, which takes into account the time-varying number of RA channels in the DQRUMA protocol

Several results for the normalized delay vs. throughput (from simulations with both random access algorithms) are given in the article.

Remarks — This protocol has the advantage that the MT is able to receive the ACK to its request packet (from the BS) almost immediately on a slot-by-slot basis. In case of a collision, the involved MTs are (quickly) aware of their failure in getting UL access, and may try retransmission earlier than with a framing scheme. A nice contribution of this protocol is the inclusion of a *piggyback* reservation field, which saves BW by avoiding further requests when the MT has more packets to transmit in its queue. This is especially useful for variable bit rate (VBR) connections.

Another advantage is that DQRUMA uses a minislot packet for access contention. In this way, the probability of receiving a packet in good shape is larger than when a longer packet is employed. Furthermore, since the length of a WATM packet is on the order of six times the length of a contention packet, the loss of contention packets does not affect the channel utilization as much as the loss of a regular packet.

A disadvantage is that DQRUMA does not make any distinction between VBR and available bit rate (ABR) services, it treats both as "bursty" traffic. Consequently, it does not consider any priority handling mechanism.

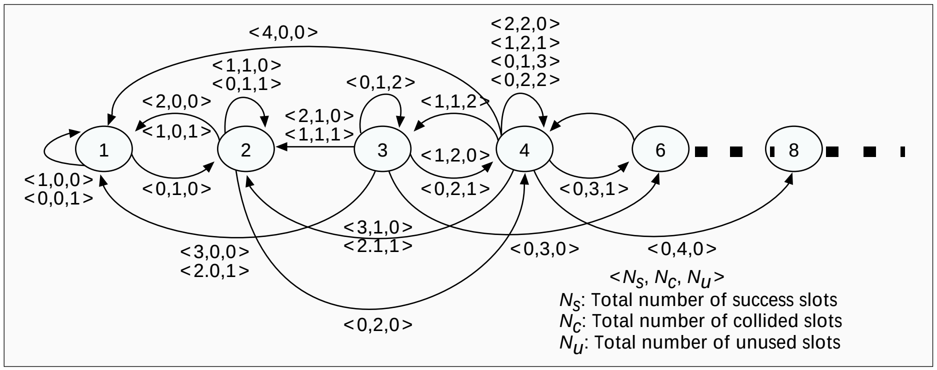
Although the authors claim that the number of minislots can be up to 25, it is worth mentioning that they are omitting the overhead needed at the PHY layer. Considering the average PHY overhead used by the IS-54, JDC, and Global System for Mobile Communications (GSM) [8] wireless systems, we get 48 bits of preamble (or synchronization) and 24 bits of guard time (9 bytes total). Thus, the length of a regular packet would be (53 + 9) = 62 bytes, while the minimum length of the access packet would be (1 + 9) = 10 bytes, resulting in a maximum of 6 minislots (62/10).

Packet Reservation Multiple Access with Dynamic Allocation (PRMA / DA)

This protocol was proposed by Kim and Widjaja in [9], and is an enhanced version of the PRMA protocol originally proposed by Goodman *et al.* in [10]. PRMA was designed for voice and data traffic only, while PRMA/DA considers constant bit rate (CBR), VBR, and data traffic.

Description of the Protocol — PRMA/DA considers a fixed length for the UL frame, which is divided into a fixed number of slots. All slots are the same size. There are four types of slots (resulting in four subframes), namely, data reservation slots, VBR reservation slots, CBR reservation slots, and available slots. The BS is responsible for determining the number of slots allotted to each type, as well as the number of slots assigned to each reserving terminal (MT). The DL frame works in the contention-free TDM format, under total control of the BS. Figure 3 shows the frame format of PRMA/DA.

After some registration procedure, when an MT has just become active (i.e., has packets to transmit), it randomly selects one of the available slots in the UL frame, and transmits one W-ATM packet (possibly in contention with other MTs). The contention method considered is slotted ALOHA. The header of the contending packet carries information about the service type (ST), a statistical parameter called the effective BW (EB), and other control fields.



■ Figure 4. *State transition diagram for the number of available slots (at a BS) in PRMA/DA.*

Depending on the type of traffic (CBR, VBR, or data), the EB, and the current availability of slots, the MAC (at the BS) will assign certain slot(s) to the succeeding MT in one of the reservation subframes for subsequent transmission. The successful MT may keep transmitting W-ATM packets until the end of the active session without any contention.

For CBR and VBR (real-time) calls, which have strict timing constraints, the unlimited repetition of contention procedures is worthless, so the protocol considers a parameter called maximum setup time ($W_{\max}$). If a contention procedure lasts for more than $W_{\max}$, the call will be discarded. The setup time for data calls not has no limitation.

As soon as the contention procedure ends, the BS notifies the contending terminals whether or not the channel access was successful. According to the results of the contention procedure, the BS increases or decreases (to a minimum of one) the number of available slots for the next UL frame, according to a particular algorithm. This is where the protocol receives its "dynamic allocation" (DA) name.

At the end of each frame, the BS transmits (in broadcast mode) information about the number of slots in each subframe as well as the number of reservation slots assigned to each (successful) reserving terminal. Also included is the exact location of the assigned slots. The header of the UL reserved slot packet contains synchronization (SYN) bits, a field called NS that indicates the current number of slots in the MT buffer, and other control bits. The NS field is used by the MAC at the BS (along with the statistical traffic parameters, EB, transmitted by the terminal) to adjust the number of reservation slots assigned to a particular MT for subsequent transmissions.

PRMA/DA considers a model with three states to represent the status of a MT. The states are *INACTIVE*, *CONTENDING*, and *RESERVING*. An MT is initially in the INACTIVE state. When a packet is generated, the MT switches to the CONTENDING state and tries to transmit a W-ATM packet according to the slotted ALOHA procedure. If the network access procedure is successful, the MT switches to the RESERVING state.

The DA algorithm uses four variables for its operation: the number of available slots (N_a); the number of slots where collisions occurred (N_c); the number of successful access slots (N_s); and the number of unused slots (N_u). The basic operation of the *DA* algorithm is as follows: assume $N_a = 1$, and assume that after a contention period the BS detects one collision. At this stage, the BS knows that at least two MTs tried to access the channel. The BS then assigns two available slots ($N_a = 2$) for the contention in the next UL frame. Having $N_a = 2$, if the BS detects two collisions (one in each slot), the BS knows that at least four MTs tried to request service and assigns $N_a = 4$ for the next UL frame.

Now let us assume that after the next contention period the BS detected one successful access ($N_s = 1$), one collision($N_c = 1$), and one unused slot ($N_u = 1$). The BS can conclude that there may be three MTs involved in a collision and assigns $N_a = 3$. In general, if the number of collisions increase, the BS increases N_a, while each time a successful access occurs, the BS decreases N_a. The operation of the DA algorithm is illustrated in Fig. 4.

Remarks — This protocol allows the MT to receive the ACK to its request packet (from the BS) relatively early (at the end of the access contention period). On the other hand, in case of a collision the involved MTs must wait until the BS announces how many available slots will be assigned for the next UL frame before the MTs can try to gain access again. This takes more time than for the DQRUMA protocol.

The main contribution of this protocol is the DA algorithm which helps resolve the contention situation quickly, and avoids the waste of BW that may occur when there are several unneeded request slots. However, one drawback is that this protocol does not use minislots for the access request. Instead, the first time an MT needs service it transmits a request message along with an information packet; so if a collision occurs, the effect on the throughput may be greater than if a small request packet had been used. This may not be important in low-traffic situations, where there may be room for several available slots, but is definitely a problem for high-traffic situations.

It is important to point out that the authors do not consider the overhead of the PHY layer (SYN and guard time) for the simulation reported in their article. They only consider the regular (5 bytes) ATM overhead.

Dynamic Slot Assignment (DSA++) Protocol

This protocol was proposed by Petras and Krämling [11]. The DSA++ protocol relies on a BS that acts as a central MAC coordinator, giving service to MTs according to the QoS and instantaneous capacity requirement of each virtual channel (VC).

Description of the Protocol — DSA++ uses (for both DL and UL channels) a variable-length frame structure called a *signaling burst*. The DL signaling burst (DSB), transmitted in broadcast mode, opens a signaling period (frame) of specific length, which may range from 8 to 15 slots. The DSB contains the following information:

- A reservation message for each UL slot of the signaling period
- An announcement message for each DL slot of the signaling period
- A feedback message for each random access slot of the previous signaling period
- Additional signaling messages (e.g., collision resolution, paging channel, etc.)

To each DL signaling period corresponds a UL signaling period of the same length. There is an offset between the starting point of each period to compensate for the round-trip propagation delay. Figure 5 shows the signaling technique used by DSA++.

The feedback messages, which are of the ternary type (empty, success, collision), are used by a fast collision resolution algorithm for capacity requests transmitted in contention

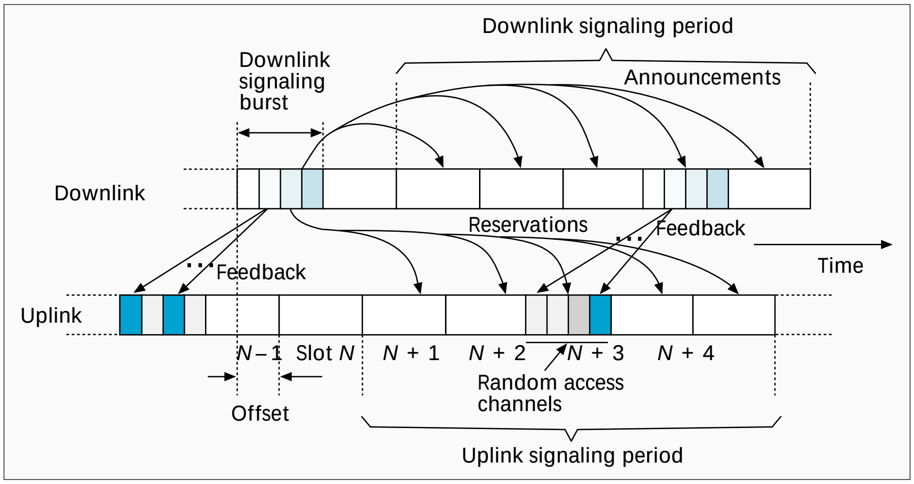


Figure 5. *The signaling scheme of the DSA++ protocol.*

slots. After the initial registration procedure, the BS allocates transmission capacity to the MTs (for both the UL and DL channels) on a slot-by-slot basis. Each slot is the size of an ATM packet plus SYN overhead.

The assignment of capacity by the scheduler is based on a priority calculation for each MT (or VC) being served. The priority is determined according to a set of dynamic parameters (DPs), which includes the number of waiting ATM packets and their due dates. The DPs are transmitted by each MT along with each ATM packet (included in the header). The BS can ask an MT to update the DPs by either polling or random access, using shorter-length slots (1/4 or 1/8 the normal size). For this purpose, the BS uses an algorithm which calculates the number of short slots that must be available in the next signaling period according to the following parameters:

- Probability of a new packet arrival at each MT in contention mode since the last transmission of their DPs
- Number of MTs in contention mode
- Throughput of the random access procedure

The priorities assigned to the ATM classes of services are as follows: CBR > VBR > ABR > UBR. For CBR and VBR classes, the protocol considers a factor called *relative urgency* to decide which MT will transmit or receive in the next *signaling period*.

An important parameter of this protocol is the delay experienced by the MT in receiving a feedback signal to its request through a UL random access slot, since the MT needs to know if its request was successful or not, to try retransmitting later in the case of collision. To reduce this delay, Petras proposes the use of a short signaling period. Each signaling period can provide from one to several random access slots, the maximum given by the size of the DSB. To further reduce the delay in getting the feedback, the DSA++ protocol uses a splitting algorithm for the backlogged MTs. The authors analyze both binary and ternary splitting algorithms.

Remarks — An advantage of this protocol is broadcast of the information that defines the next signaling period in a single DL burst (UL slot assignment, DL slot assignment, and ACKs for previous packets or access requests). This releases all other slots in the DL signaling period, allowing the BS to implement an MT power control algorithm if needed.

This advantage must be weighed against the risk of losing the broadcast packet, which means that a whole signaling period would be lost. Otherwise, the loss of a control packet addressed to a specific MT would not affect the throughput as much. Even though there are no collisions in the DL channel, since the BS is the only one that transmits in the relevant cell, a packet may be lost due to interference from other cells (cochannel interference) or a deep fade.

Another advantage of this protocol is that it allows a UL slot to be divided into up to four short slots to be used for access request in contention mode. This feature, along with the use of the *Priority Splitting algorithm*, helps to resolve the access contention quickly and efficiently.

Dynamic TDMA with Piggybacked Reservation (DTDMA/PR)

This protocol was proposed by Qiu *et al.* [12]. DTDMA/PR is an extension of the DTDMA protocol originally proposed by Raychaudhuri and Wilson to be used in an ATM-based wireless personal communications network (PCN) [13].

Description of the Protocol — DTDMA/PR considers a fixed-length frame, with minislots for reservation (in the UL channel) and ATM-packet-size slots for transmission of user information. The UL frame is divided into three subframes, the first for reservation minislots, the second for long-term reservable slots, and the third for short-term reservable slots. The boundary between the long-term and short-term reservable subframes is movable according to the traffic volume being handled.

This protocol considers three types of traffic, with all packets having the same length:

- CBR packets, generated periodically during the active period (the protocol considers some sort of voice activation detector).
- VBR packets, which are also generated periodically during the active period, but in groups of different size. The number of packets in each group is a random variable with certain probability distribution function.
- ABR packets, generated in bursts.

The frame length is chosen according to the voice encoder/decodeer (codec) characteristics, with the intention of

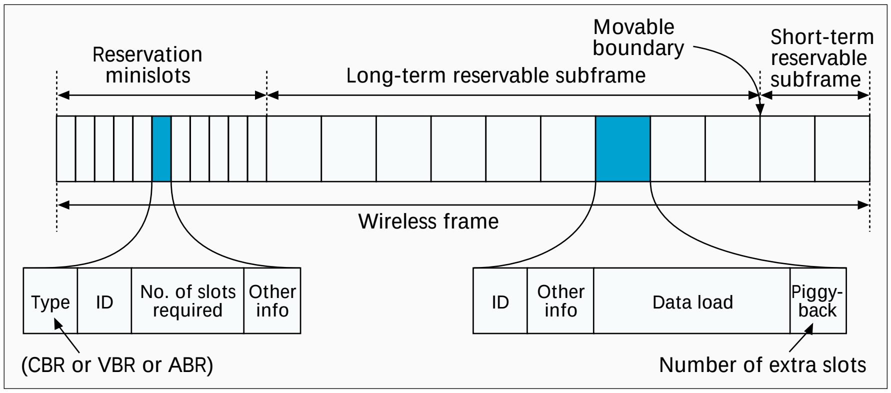


Figure 6. *The frame structure of the DTDMA/PR protocol.*

facilitating the provision of CBR services. Otherwise, the slot size is considered equal to the size of an ATM packet (53 * 8 + overhead bits).

The operation of the DTDMA/PR protocol is as follows (assuming the MTs have already been registered at the BS): when a CBR (VBR or ABR) source generates a new active period, it will randomly choose a mini-slot at the beginning of the next frame and will transmit a reservation packet (perhaps in contention with other MTs). At the end of the reservation period, the BS will send a broadcast message containing the IDs of the MTs that were successful in making a reservation, the number of slots assigned to each MT, and the slot positions assigned (in either the long-term or short-term reservable subframe). Figure 6 shows the frame structure for the DTDMA/PR protocol.

Reservations for CBR and VBR can happen only in the long-term subframe, while reservations for ABR can happen only in the short-term one. The CBR and VBR terminals that were successful in accessing the BS can keep using the same time slots as long as they have more packets to send (within the same active period), while ABR terminals have to release the assigned slot as soon as they finish transmitting a packet.

Both CBR and VBR services are considered delay-sensitive, so the corresponding packets myst be discarded if they exceed some time limit. Meanwhile, the ABR traffic is considered delay-insensitive, and the ABR packets can be buffered until the BS assigns a slot for their transmission.

Since the authors assume no channel errors, the reasons for reservation failures are either reservation packet collisions or excessive traffic. They also assume that there is no propagation delay involved in the reception of the ACKs to the reservation requests, and no processing time is required by the BS in responding to those requests.

A mechanism to guarantee service to VBR traffic is included. This consists of sending a piggyback reservation message along with the VBR packet when the number of assigned slots is less than the number of packets generated in the current slot. The slots eventually assigned by the BS in response to a piggyback request must be released at the end of the current frame. To keep the unused slots at the end of the frame, a mechanism of slot reordering and reassignment has been implemented.

Remarks — One advantage of this protocol is that it considers the use of a piggyback reservation (previously proposed in the DQRUMA protocol), which is especially useful for VBR VCs. Another advantage is the use of minislots for reservation so that if an access packet collides, there is not much waste of BW.

A contribution of this protocol is the consideration of two types of reservable subframes with movable boundary: the long-term subframe, meant to be used by CBR and VBR connections, and the short-term subframe (whose slots have to be released after a one-packet transmission), aimed at ABR connections. This may be used to provide more BW to CBR and VBR services according to the current needs.

A drawback of this protocol is that it does not take into account the different constraints of the QoS involved in each VC. Therefore, in case of two request packets colliding from MTs with different delay constraints, the probability of retransmission in the next frame is the same for both. Hence, the probability of successfully accessing the BS is the same for all MTs since there are no priorities involved.

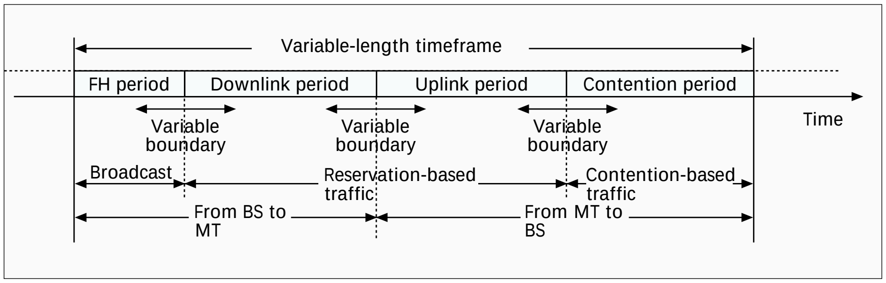


Figure 7. *MASCARA timeframe structure.*

TDD Protocols

These protocols use only one carrier frequency to communicate both ways, from the BS to MTs and from MTs to the BS. They save some hardware in the MTs since both the transmitter and receiver operate at the same frequency, but generally add extra delay due to the turnover between transmitter and receiver modes. The protocols analyzed in this category, again in order of publication, are MASCARA, PRMA/ATDD, and DTDMA/TDD.

Mobile Access Scheme Based on Contention and Reservation for ATM (MASCARA)

This protocol was proposed by Bauchot *et al.* [14] as the MAC protocol for the W-ATM Network Demonstrator (WAND) project being developed with the support of the European Community (EC).

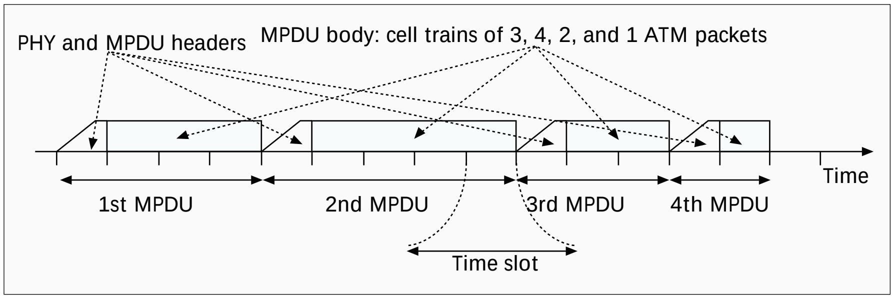
Description of the Protocol — The MASCARA protocol operates in a hierarchical mode by means of a master scheduler (MS) in the BS (called *access point*) and a slave scheduler at each MT. The DL traffic is transmitted in TDM mode, while the UL packets are transmitted in a mix of reservation and contention modes.

MASCARA is based on a variable-length timeframe (TF), which consists of two subframes, one for the UL channels and the other for the DL channels. The DL subframe is divided into two periods, the frame header (FH) and down periods. The UL subframe is also divided into two periods, up period and contention. All the periods are of variable length, and all are further subdivided into a variable number of time slots. The structure of the MASCARA frame is shown in Fig. 7.

The TF always begins with an FH, which is used by the BS to broadcast to all MTs a descriptor of the current TF (including the lengths of each period), the results of the contention procedures from the previous frame, and the slot allocation for each active MT. The MTs use the UL contention slots to transmit reservation requests (for subsequent frames) or some control information. Since most of the traffic can be predicted by the BS, use of the contention-based slots is reduced to a minimum.

Each of the periods within a frame has a variable length that depends on the instantaneous traffic in the wireless link. The periods that operate in reservation mode may collapse to zero slots. The contention period is always maintained to at least some minimum number of slots, since an MT may ask for registration at any time by sending a control packet.

For handling the transmission process, MASCARA defines the concept of a “cell train,” which is a sequence of ATM packets belonging to one MT, ranging from 1 to *n*, with a common header. The length of a time slot as well as the length of the MPDU header are defined as the length of an ATM packet (53 bytes). The MPDU header includes the



■ Figure 8. *MPDU structure relative to time slots in MASCARA.*

SYN bits needed at the PHY and the specific bits of the header. The payload of a cell train is called a *MASCARA protocol data unit* (MPDU). Figure 8 shows the structure of the "cell train."

The MS takes into account the service class of the current ATM VCs, the negotiated QoS, the amount of traffic, and the number of reservation requests to determine the type and volume of traffic that will be transmitted in the following frame. This latter information is kept in a slot map which specifies the size of the three periods (downlink, uplink, and contention), as well as the assignment of time slots (in the current TF) to each involved MT.

The BS broadcasts the slot map within the FH at the beginning of each TF. With the aid of this slot map, each MT can determine if it will be allowed to either receive or transmit MPDUs in the current frame. This mechanism allows the MTs to perform some power-saving procedure, such as entering a "sleeping" mode when there is no traffic scheduled for it.

The MS uses an algorithm called Priority Regulated Allocation Delay-Oriented Scheduling (PRADOS) to schedule transmissions over the radio interface. This algorithm is based on the priority class, the agreed characteristics, and the delay constraints of each active connection. Passas *et al.* describe this algorithm [15].

PRADOS introduces priorities for each connection according to its service class as specified in Table 1 (a higher number indicates higher priority).

PRADOS combines priorities with a leaky bucket traffic regulator (LBTR). The LBTR uses a token pool that is introduced for each connection. The generation of tokens happens at a fixed rate equal to the mean ATM packet rate of each VC. The size of the pool is equal to the maximum number of ATM packets that can be transmitted with a rate greater than the declared mean. Starting from priority 5 and ending with priority 2, the scheduler satisfies requests for UL and DL as long as tokens are available. For every slot allocated to a connection, a token is removed from the corresponding pool.

Remarks — The introduction of the concept of a *cell train* is a good contribution of this article, since it provides variable capacity to MTs in multiples of slots that have the standard size of one ATM packet (53 bytes). Although not totally defined, the authors consider a wireless data link control (WDLC) sublayer to take care of erroneous or lost ATM packets. The WDLC technique will depend on the constraints imposed by the QoS parameters of the different services. Another important contribution of this protocol is the proposed PRADOS algorithm for the master scheduler, since by deciding on the allocation of slots on a frame-by-frame basis helps in the fulfillment of the negotiated QoS parameters for each connection.

A disadvantage of this protocol is that the size of the access request packet, which may be in contention with other MTs, is large (equivalent to two ATM packets, one for SYN and overhead, the other for control information). In the case of high traffic, where the probability of collision increases, this could result in an important reduction of throughput.

Another drawback of this proposal is that the authors have not yet decided on the contention procedure (they are investigating slotted ALOHA and the Stack algorithm). However, they do not mention anything about the optimization of the time it will take to access the UL channel, which is critical for CBR services.

Last but not least important is that a variable-length frame introduces an extra difficulty in assigning capacity to MTs with CBR services. Assuming the case of a voice (64 kb/s) call, if the frame length (in milliseconds) is less than the time to fill an ATM packet (~6 ms), there may be frames where no slots need be assigned. Otherwise, if the frame length is longer than 6 ms, it might be necessary to assign more than one slot in a frame for this call.

Packet Reservation Multiple Access with Adaptive Time-Division Duplex (PRMA/ATDD) Protocol

This protocol was proposed by Priscoli for the MEDIAN system [16]. The MEDIAN system is a project being developed in Europe as part of the ACTS program, with partial support of the EC. The aim of the project is to develop a high-speed (~150 Mb/s) wireless network compatible with the B-ISDN ATM network, to operate in an indoor environment using the 60 GHz band.

Description of the Protocol — The PHY of the MEDIAN system is based on the orthogonal frequency-division multiplexing (OFDM) technique combined with a TDD scheme. Implementation of the protocol relies mostly on software which is concentrated in the BS.

The TDD frame is of constant length equal to 64 slots, although the UL and DL subframes are of variable length. The DL subframe (DLS) occupies the first part of the frame, and the UL subframe (ULS) occupies the second portion. The basic information unit in PRMA/ATDD is called an *extended cell* (or *slot* for simplicity), which consists of an ATM packet (53 bytes) plus the overhead needed for wireless transmission, resulting in a total of 1024 bits. Figure 9 shows the frame structure of this protocol.

The first slot of the frame is used for synchronization, while the second slot is intended to carry broadcast information. The other 62 slots are used to carry information packets from the BS to MTs in the DLS, and from MTs to the BS in the ULS. The broadcast information includes:

- The number of slots in the DLS (which defines the number of slots in the ULS)

Priority number	Service class
5	CBR (constant bit rate)
4	rt-VBR (real-time variable bit rate)
3	nrt-VBR (non-real-time variable bit rate)
2	ABR (available bit rate)
1	UBR (unspecified bit rate)

■ Table 1. *Priority numbers assigned to the services in MASCARA.*

- The assignment of each slot for the MTs
- Signaling related to PRMA parameters and call setup or termination

A radio virtual call identifier (RVCI) is used to relate the slots with their associated calls in the broadcast packet. This way, there is a unique mapping between the RVCI and the VC identifier (VCI)/virtual path identifier (VPI) inside the wireless system. The RVCI field needs only 5 bits to address the maximum number of calls (30) handled by a BS.

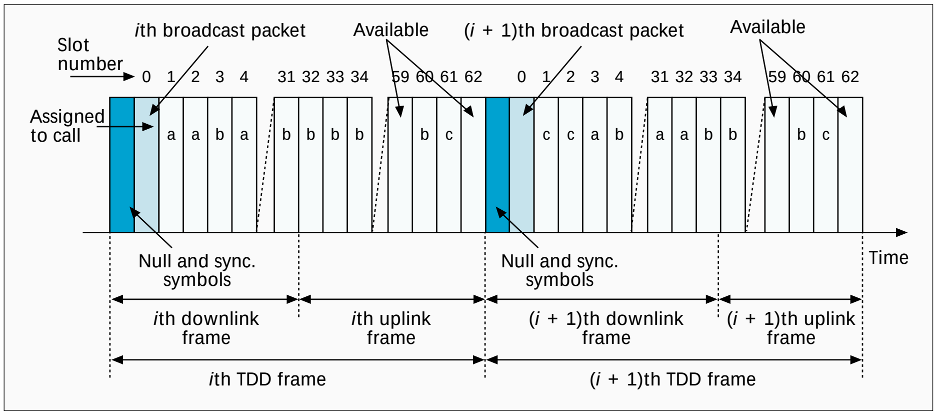


Figure 9. *PRMA/ATDD frame format.*

The BS functional architecture consists of uplink and downlink buffers, serial-to-parallel and parallel-to-serial converters, and several network entities (NE). There are four NEs that are directly related to the MAC layer.

Static List Handler — The SLH determines the call static parameters to be stored in the static list (SL), which is updated only at call setup. Each record of the SL refers to a call in progress, and includes the next four fields: RVCI, $\Delta_{\text{max-up}}$, $\Delta_{\text{max-down}}$, and $R_{\text{max-up}}$. RVCI is the identifier of the call to which the record refers, $\Delta_{\text{max-up}}$ and $\Delta_{\text{max-down}}$ are the UL and DL maximum delays allowed by the VC, and $\mathrm{R}_{\text{max-up}}$ is the UL maximum bit rate.

Dynamic List Handler — The DLH controls a list of records, each one containing information about a specific ATM packet waiting in the BS buffer (or in an MT buffer), to be transmitted in the air interface. Each record has the following fields: UD, RVCI, and t_{max}. UD is a bit that indicates whether the ATM packet to which the record refers is a UL or DL packet. The parameter t_{max} defines the last time at which the packet must be transmitted in order to avoid its loss due to excessive waiting time.

When a DL packet arrives at the BS, it is stored in the DL buffer. The BS deduces the RVCI value from the VCI/VPI field in the header, and records this value in the DLH. The DLH uses the information contained in the SLH to compute t_{max}. After this, the BS inserts the corresponding new DL record in the dynamic list (the DL in DLH).

When a UL packet arrives at the BS, it is momentarily placed in the UL buffer in order to deduce the VCI/VPI from the RVCI field. After the DLH receives this VCI/VPI, it uses the information stored in the SLH to construct the appropriate record that will be added to the DL. The DLH receives from the PRMA parameter computer (PPC) the number of slots that will be available, termed $S_{\text{av}}(i)$, for contention in the next UL frame. The DLH then assigns the remaining Sav(i)-62 useful slots to the packets that occupy the corresponding records in the DL, as long as they have not expired.

Broadcast Packet Generator — This entity generates the broadcast packets, according to the information received from the DLH (DL frame duration, UL/DL slot assignments, and PRMA state transitions), from the PPC, and from the BS signaling handler (call setup/termination related signaling).

PPC — This entity uses the data provided by the DLH to compute, at each frame, the most appropriate values for the permission probabilities related to the various transport services (CBR, VBR or ABR), and to the number of available slots per frame. These computations take into account both the instantaneous traffic level and the QoS requirements of currently active connections.

Figure 10 shows the functional architecture of the PRMA/ATDD protocol that runs in the BS; the figure also includes a brief description of the signals handled.

Remarks — A contribution of this protocol is the idea of using two list handlers (LHs) for the MAC protocol in the BS: the static LH (with parameters related to the whole duration of the call) and the dynamic LH (with parameters related to the current packets in the buffer). The DLH helps decide which Mts will be served in the next frame according to the expiration time of the buffered packets. These lists are used to assign priorities to ATM packets according to their expiration risks.

An advantage of this protocol is the use of a fixed-length frame, which facilitates the provision of CBR services by assigning a fixed number of slots in each frame. Nevertheless, the UL (and correspondingly, the DL) subframe varies dynamically, in response to the traffic demand.

Similar to PRMA/DA, a disadvantage of this protocol is the use of full-size slots instead of minislots for access request. This is inherited from the original PRMA protocol, which was not designed for the W-ATM network.

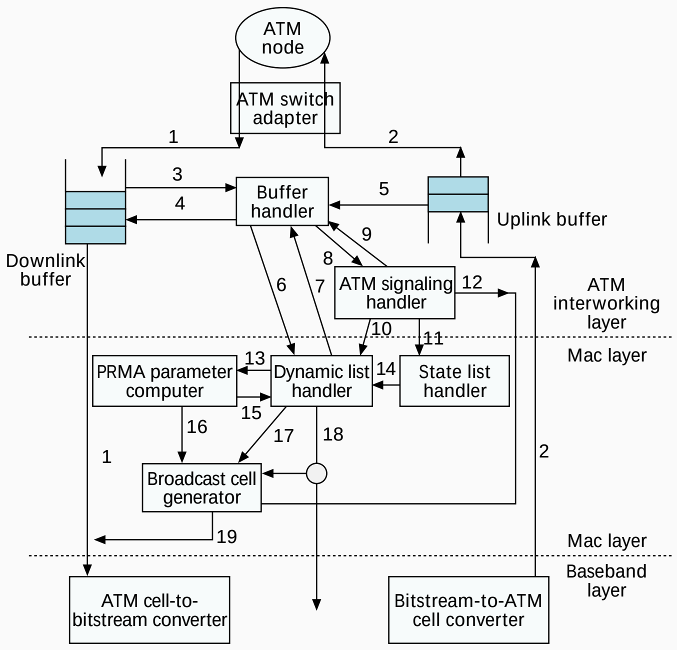
Dynamic TDMA with Time-Division Duplex Protocol (DTDMA / TDD)

Dynamic TDMA was proposed by Raychaudhuri *et al.* [17], as part of the WATMnet prototype system developed at C&C Research in NJ. More detail on the MAC protocol parameters is given by Xie et al. in [18].

Description of the Protocol — This protocol is based on a TDMA/TDD structure with a fixed-length frame. The DL subframe is handled in simple TDM format, transmitted in a single burst. It consists of two parts. The first part contains control and feedback (ACK) signals, while the second part is used for data transmission from BS to MTs.

The UL subframe is handled in a dynamic format and divided into four slot groups: a group for request (mini) slots, which uses slotted ALOHA; a dynamic allocation group, which carries ABR and/or UBR traffic; a fixed and shared allocation group, which carries VBR traffic; and a fixed allocation group for CBR traffic. Figure 11 shows the dynamic TDMA/TDD frame format.

Even though the total frame length is fixed, the boundary between DL and UL subframes varies gradually, according to



Signal no.	Basic information carried by the signal
1	ATM packets coming from the ATM network
2	ATM packets forwarded to the ATM network
3	VPI/VCIs of the arrived DL ATM packets
4	Buffer addresses of the DL ATM packets to be forwarded to the BB layer
5	VPI/VCIs of the arrived UL ATM packets
6	RVCIs of the arrived UL/DL ATM packets
7	RVCIs of the DL ATM packets to be retrieved from the DL buffer
8–12	Signaling information
13	Dynamic list related information
14	Static list related information
15	Number of available slots per frame
16	Permission probabilities
17	UL/DL slot assignments; PRMA state transitions (ACK/NACK)
18	DL frame duration
19	Broadcast ATM packets

■ Figure 10. *BS functional architecture in PRMA/ATDD.*

the traffic experienced by the network. Inside the subframes, the boundaries between the different slot groups are also movable.

For the UL subframe, the R-B control packets contain 5 bytes of information plus 2 bytes of CRC. The data packets contain the original 53 byte ATM packet with 2 bytes from the Header substituted by a wireless Header, plus 2 bytes for CRC. Each one of the two types of packets needs an additional modem preamble of 16 bytes for synchronization and equalization purposes.

For the DL subframe, only one modem preamble is needed at the beginning of the subframe, since the transmission is done only by the BS in a broadcast mode. A single W-ATM ACK message can acknowledge up to 20 packets.

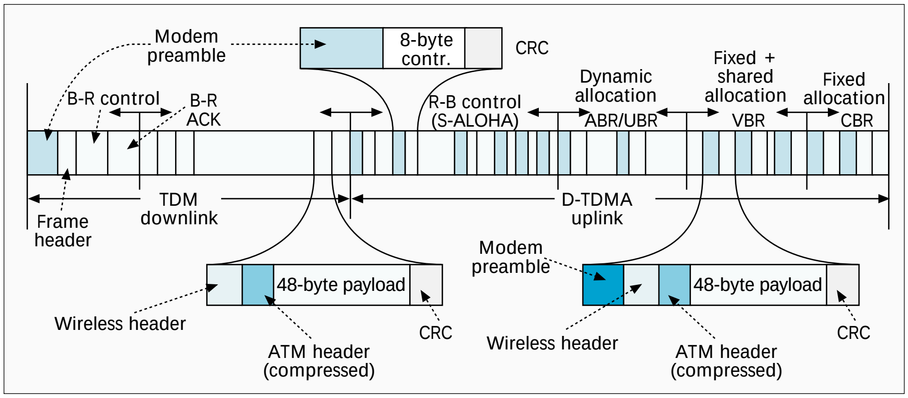
When an MT has packets to transmit, it sends a request through a control slot, possibly in contention with other MTs. At the beginning of the next DL subframe, the BS transmits the slot allocation information along with the ACKs and other control information.

For the case of CBR VCs, the allocation is done once per session. For the case of ABR/UBR VCs, it is performed on a burst-by-burst basis with dynamic reservation of slots from the ABR/UBR group and from the unused CBR or VBR slots. For VBR VCs, the allocation is accomplished on a fixed shared basis, with some slots assigned for the duration of an active period, plus some extra slot(s) assigned according to a usage parameter control (UPC)-based statistical multiplexing algorithm.

In case more than one slot is needed for ABR/UBR VCs, contiguous slots are assigned to reduce overhead. VBR and CBR calls can be blocked, while ABR/UBR calls are always accepted subject to appropriate rate flow control.

Functionally, the MAC protocol can be divided into two components: supervisory MAC (S-MAC), and core MAC (C-MAC). The S-MAC at the BS performs channel scheduling for both the UL and DL channels for all services (CBR, VBR, and ABR). Also, the S-MAC builds a schedule table based on the relevant QoS parameters. Finally, the S-MAC takes care of call admission control.

The C-MAC serves as the interface between the data link control and PHY. According to the schedule table supplied by the S-MAC, the C-MAC multiplexes and demultiplexes the packets for transmission into the wireless channel for each VC.



■ Figure 11. *Dynamic TDMA/TDD MAC frame format.*

Remarks — One advantage of this protocol is the division of a frame into small (8-byte) slots, which allows it to use one slot for random access transmission of control packets (from MT to BS), and to assign several slots (seven for an ATM packet) to the different services (CBR, VBR, ABR), according to the traffic demand and QoS involved.

Another advantage is that it includes a data link control (DLC) layer which handles some functions that complement the tasks of the MAC protocol. For example, to resolve the delay constraint imposed by the CBR services, the DLC uses a

	DQRUMA	PRMA/DA	DSA++	DTDMA/PR	MASCARA	PRMA/ATDD	DTDMA/TDD
Physical layer type	FDD	FDD	FDD	FDD	TDD	TDD	TDD
Frame type	No frame	Fixed	Variable	Fixed	Variable	Fixed	Fixed
Frame size	—	6 ms	8–15 slots	16 ms	—	64 slots	2 ms
Size of access contention slot	Fraction of ATM pkt.	Same as ATM pkt.	1/4 of ATM packet	Fraction of ATM pkt.	2 ATM packets	128 bytes	1/7 of ATM packet
QoS support	VBR	BW-related: voice,video,data	CBR, VBR, ABR	CBR, VBR, ABR	CBR, rt-VBR nrt-VBR, ABR, UBR	Delay-related	CBR, VBR, ABR
Relative algorithm complexity	Low	Medium	Medium	Low	High	High	High
Relative communication complexity	High	Low	Medium	Low	High	Medium	Medium
Channel utilization efficiency	High	Medium	High	High	Medium	Medium	High
Channel impairments analysis	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered	Log-normal fading
Control overhead	Low	Medium	High	Medium	High	High	Medium
Random access technique	S-ALOHA, bin. stack	S-ALOHA	Splitting alg. (2 and 3)	S-ALOHA	Not defined yet	S-ALOHA (p_{prob} = q)	S-ALOHA
Relative complexity of providing CBR services	High	Low	Medium	Low	Medium	Low	Low
Call admission control	No	Yes	No	No	Yes	No	No

Table 2. *Comparison of the protocols.*

first-in first-out (FIFO) buffer to ensure that ATM packet jitter will be kept under acceptable limits. Another useful idea introduced is to let the DLC handle retransmission of erroneous CBR packets by using ABR channels without disturbing continuous transmission in the CBR reserved channel.

This protocol may be upgraded by adding an algorithm to handle retransmission of reservation packets (which are handled with the traditional slotted-ALOHA protocol), to give priority to MTs requesting service for CBR or rt-VBR traffic.

Conclusions

Several recently proposed MAC protocols for W-ATM were reviewed. It appears that the protocols which use FDD in the PHY can deal with the access contention procedures more quickly. However, the use of only one carrier frequency (as in the protocols that use TDD) can be advantageous in some situations where frequencies are scarce.

When considering the noise, fading, and high interference characteristics of most wireless environments, it is important to contemplate a method for fast collision resolution in the random access stage. In this context it is convenient to use small slots (minislots) for the random access channel(s) so that collisions do not produce significant throughput degradation.

It also appears to be convenient to handle the ACKs to the access requests (from the BS to the MTs) on a slot-by-slot basis. For the protocols where the BS sends the result of the contention procedure on a frame-by-frame basis, the MTs involved in a random access process have to wait until the next frame to know the result of the contention process; after that (in case of failure) they may try another access. This may represent a waste of BW, especially in medium traffic situations (where there may be some free slots). It may also represent a waste of time, which may be critical in the case of an MT that just handed off and is using a CBR (or VBR) delay-sensitive service.

The handling of ACKs on a slot-by-slot basis is easier to implement in an FDD system than in a TDD one, which may indicate an advantage of FDD over TDD. However, this advantage must be weighed against the disadvantage that FDD requires two carrier frequencies.

An advantage of TDD over FDD is that when the DL traffic is bigger than the UL traffic, TDD uses BW more efficiently by allocating most of the slots to the DL subframe. DL traffic can be larger than UL traffic when several MTs are downloading huge files or receiving video on demand.

It is also important to consider the QoS constraints for the different services (CBR, rt-VBR, nrt-VBR, ABR, and UBR), which must be reflected in different priorities assigned to the request packets in the collision resolution algorithm.

To summarize the advantages and disadvantages, in Table 2 we present an overall comparison of some of the characteristics of the protocols reviewed. Some of the entries are based on subjective judgments rather than formal analysis. Relative communication complexity is based on the load imposed on the MT radio equipment in order to get synchronized and keep track of the slots. Channel utilization efficiency takes into account the size of the access contention slot.

Finally, a more realistic evaluation of the performance of the proposed MACs would need to take into account the specific impairments of the RF channel, which to our knowledge has only been done in the DTDMA/TDD protocol. To partially compensate for these impairments, some form of forward error correction should be used, at least in the access and control signals.

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