Design Principles for a MAC Protocol of an ATM Air Interface

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Abstract: *The protocol stack of a wireless ATM system is currently under investigation in several research projects. A lot of MAC protocols have been proposed for such an ATM air interface. Most of the protocols are only varying in some details. With this paper we try to extract some fundamental guidelines for the development of MAC protocols for specific wireless ATM systems.*

1 Introduction

After the success of the *asynchronous transfer mode* (ATM) in the area of multimedia networks, a demand for the transparent integration of wireless ATM terminals into fixed ATM networks has become visible during the last years [14]. In 1995 ATM-Forum and ETSI have established special *wireless ATM groups* which are currently investigating requirements and system architectures for a wireless extension of ATM networks. In general, the users of wireless ATM terminals request the same functionality and *Quality of Service* (QoS) as users of wired terminals. Thus, the protocol stack at the ATM air interface has to behave like a usual ATM multiplexer [8]. This *virtual* ATM multiplexer around the air interface has to coordinate the access to the shared radio resources in such a way that the QoS of all ATM service classes can be guaranteed for each established virtual channel connection (VCC).

Wireless ATM (WATM) systems are conceivable in a large variety of applications, such as public or private access networks for substitution of cable-based infrastructure (Radio in the Local Loop), as indoor or outdoor broadband and multimedia cellular radio systems, wireless ATM-LANs or ad-hoc networks. This large range of applications leads to a variety of types of WATM systems differing in services and the terminal mobility, according to the specific scenario. It can be assumed that, depending on the application, different frequency bands with differing bandwidths, including also infrared, will be used in the future. As a result, various modulation and transmission schemes exist for the wireless link, so that we cannot assume a homogeneous standard of WATM modems. Concerning the structure of the logical channels and the access protocols at the air interface, a scalable, standardized solution is desirable.

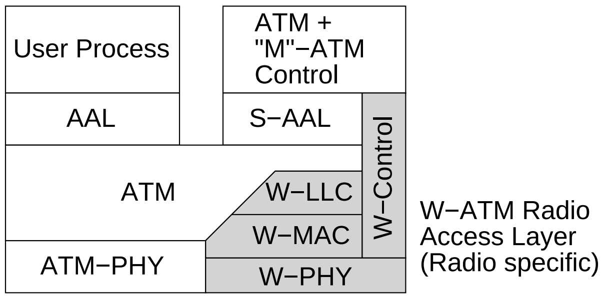

Figure 1: Protocol stack of the virtual ATM multiplexer at the ATM air interface

Inside the virtual ATM multiplexer around the air interface, the physical layer and parts of the ATM layer are replaced by a wireless physical layer as well as an additional data link layer consisting of a *logical link control* (LLC) and a *medium access control* (MAC) sublayer (cf. Fig. 1).

The MAC protocol at the ATM air interface has to realize a fair statistical multiplexing according to the negotiated QoS. Special attention has to be payed to the *maximum cell delay* of real-time oriented (CBR, VBR) services. Several proposals for MAC protocols can be found in the literature [1, 3, 6, 7, 11, 12]. It can be seen that most of this protocols are using the same concepts and are only varying in details. In our paper we like to extract the common aspects and give design rules for the synthesis of a MAC protocol for the specific scenario of a cellular network.

2 General aspects of a WATM MAC protocol

In the considered scenario of a cellular network, the virtual ATM multiplexer of one radio cell, consisting of several wireless terminals and a central base station, can be modelled as a distributed queueing system. Due to low data rates (e.g. 50.000 ATM cells per second per frequency channel [13]) compared to normal ATM multiplexers, the observance of the negotiated QoS for each VCC is only possible, if an ATM cell scheduler based on static or dynamic priorities is employed [10]. Thus, the assignment of slots to virtual channels by the MAC protocol has to be controlled by a central instance. In the system considered, the ATM cell scheduler is running in the base station.
The following aspects have to be considered, when designing a MAC protocol with the above mentioned features:

Access mode: In general TDMA, FDMA, CDMA or a hybrid combination of these schemes seems to be possible. Because of the statistical time division multiplexing in ATM networks, and because of the high bandwidth on the physical channel, a hybrid TDMA/FDMA scheme seems to be the natural candidate for a WATM system. But also unconventional solutions like in [5] should be considered.

Duplexing scheme: Two duplexing schemes are under discussion for WATM systems, time division duplexing (TDD) and frequency division duplexing (FDD). With FDD, the bandwidth of one band is halved compared to TDD. This makes modem design easier. On the other side, several components of the modem have to be doubled. TDD has the disadvantage of an additional overhead for transceiver turn-around time. But this is compensated by the gain in efficiency resulting from the statistical multiplexing between uplink and downlink especially in scenarios with asymmetric load. The decisive argument may be the targeted frequency band. Because of the required guard band of several GHz between uplink and downlink, FDD seems only be possible in higher GHz bands (e.g. 40GHz, 60GHz). For HIPERLAN Type 2 operating at 5GHz, TDD has been chosen.

Capacity allocation scheme: The allocation of channel capacity to VCCs can be performed in a static or dynamic way or a combination of both. Static allocation schemes have the advantage that long term capacity assignments are less prone to transmission errors than the frequent signaling with dynamic schemes. But dynamic schemes seem to be more appropriate for the statistical traffic load in ATM networks. Details will be discussed in section 3.

Signaling of slot assignments: If the allocation of capacity to VCCs or wireless terminals has once been determined by the capacity allocation scheme or ATM cell scheduler in the base station, the slot reservations have to be signaled to the wireless terminals. The solutions highly depend on the chosen capacity allocation scheme. Usually, reservation messages for a specific time interval (e.g. for one frame or signaling period) are grouped in a signaling burst and broadcasted over the downlink.

Transmission of capacity requests: To ensure the correct execution of a service strategy, the scheduler has to be informed frequently about the status of the queues inside the wireless terminals which is performed by transmitting capacity request messages over the uplink. Detailed considerations on polling or contention based schemes can be found in [9, 10].

Service strategy of the ATM cell scheduler: The problem of determining an optimal transmission order of ATM cells is a well known problem in fixed ATM networks and has been investigated in much detail [4]. The algorithms have to be adapted to the specific conditions at the air interface. Espicially the fast and efficient transmission of acknowledgements has to be considered by the scheduler [8]. Furthermore, the scheduling of ABR cells can be combined with the execution of generic flow control in order to avoid the load of looped back resource management cells [2].

In section 4 we finally discuss some optimizations of a MAC protocols targeting on the reduction of the overhead produced by the physical layer.

3 Capacity allocation schemes

We assume a TDMA channel with a slot length τ_{slot} able to carry one ATM cell with some additional MAC and LLC signaling information in the header and with the necessary overhead of the physical layer for synchronization, FEC, guard interval, etc. [7].
In order to coordinate the access of the wireless terminals (WT) to the shared radio channel, the assignment of slots to WT has to be performed according to a capacity allocation scheme. Circuit switched synchronous time division multiplexing (STDM) schemes used in conventional, second generation cel-

lular systems, are well known for their simplicity, stability and low signaling overhead. These schemes are working very efficient especially for CBR services. On the other hand, bursty services like VBR or ABR require capacity on demand with asynchronous, statistical multiplexing on the radio channel. This is much harder to coordinate and produces a high signaling overhead.
To distinguish between these schemes the following definitions are given:

Vertical reservation: The slots on a TDMA channel are organized by frames of length N. With the assignment of a slot position of the frame to a WT, a discrete and constant capacity is available for all following frames without further signaling. This corresponds to the assignment of a channel in an STDM scheme.

Horizontal reservation: Capacity is assigned slot-by-slot realizing asynchronous multiplexing. With the assignment of a slot, a WT is allowed to transmit one ATM cell. Thus, one reservation message is in general necessary for each slot.

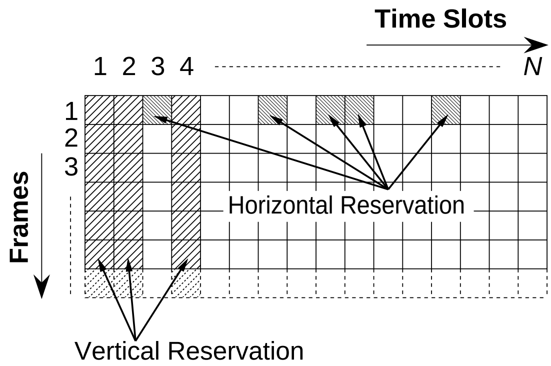

Figure 2: Vertical and horizontal reservation

Taking into consideration the variety of ATM service classes, a combination of vertical and horizontal reservation seems to be useful as indicated in Fig. 2. In the following we evaluate the performance of both schemes for specific applications.

3.1 Pure vertical reservation

With vertical reservation one or several slot positions of the frame are associated with a WT by exchanging signaling messages once. Without any more signaling, these slots are reserved for all following frames. Any change of reservations has to be signaled again. Therefore, the signaling overhead decreases with long time connections. Having a frame of constant length N, channels with an integer multiple of the basic capacity $c_b = c_c/N$ are available by occupying one or multiple slot positions.
Vertical reservation corresponds to STDM schemes and is most profitably used in communication networks offering circuit switched CBR services, like ISDN or GSM. Accordingly, in WATM systems it also seams to be very useful for CBR services. It is optimal for data sources working synchronous to the slot period of the channel. In this case the data rates of the source and of the channel are identical and isochronous. But unfortunately, in ATM networks there is no synchronization of the data source and the slot clock on the physical medium. Thus, it is necessary to round up the capacity demands to the integer multiple of the basic capacity c_b. This leads to a waste of capacity, if the data rate is low compared to the physical channel capacity. It is reasonable to choose c_b according to the data rate of the most common used narrowband service, which is the 64kb/s PCM speech codex.

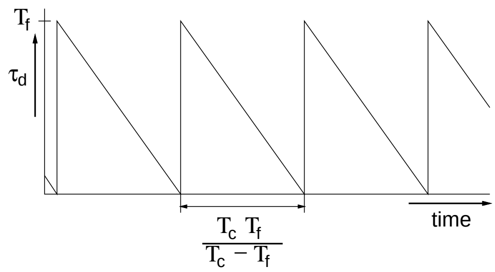

Figure 3: Queueing delay for CBR services with pure vertical reservation

A considerable problem is caused by the unavoidable asynchronity between the source of CBR ATM cells and the slot clock on the physical medium. This leads to a variable transmission delay caused by the time waiting for the next possible transmission slot. As shown in Fig. 3 this delay decreases from a maximum value of one frame length $\tau_{d_{max}} = T_f$ down to zero in a periodic way. The frequency f of this curve is given to $f = 1/T_f - 1/T_c$ with $1/T_c$ being the ATM cell generation rate ($1/T_c$ is also called packetizing delay, 6ms with 64kb/s PCM) and $1/T_f$ being the frame frequency.
The AAL in the receiver will restore the isochronity of the received ATM cell stream by delaying all received ATM cells up to their maximum delay, which is in the order of the packetizing delay. Thus, $\tau_{d_{max}}$ gives the effective maximum delay of the air interface and is a critical parameter of the overall system performance.

This additional delay in the order of 6ms is not acceptable. Furthermore, the above described scheme does not allow retransmissions in case of transmission errors. Thus, pure vertical reservation is not suitable for CBR services. For the transmission of other real-time services like VBR, pure vertical reservation is again not useful, since it contradicts the statistical multiplexing of ATM.

3.2 Horizontal reservation

Horizontal reservation needs a reservation message consisting of one address for each slot. This leads to a constant signaling overhead. The determination of horizontal slot reservations takes place on a short term base, e.g. for the length of one frame with a signaling slot at the beginning carrying all reservation messages for the actual frame (also called *signaling period* to avoid confusions with an STDM frame [7]). With this scheme dynamic requirements are able to be considered, enabling the application of dynamic priorities in the ATM cell scheduler [8]. The loss of one signaling message is less critical than using vertical reservation, since each signaling is only valid for one frame and will be renewed in the next one.

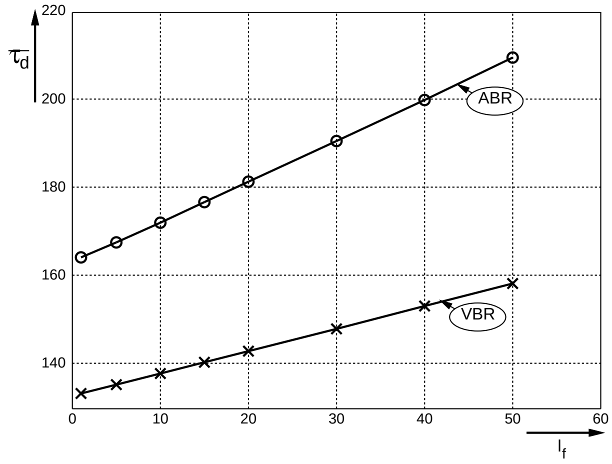

Figure 4: Mean delay for different frame lengths

The performance evaluation is done by a simplified model enabling the determination of the influence of the frame length on average delays. A fixed frame length is assumed with slots being assigned to certain WTs during the start of each frame by considering the actual capacity demands. The first slot of each frame is used for signaling the respective slot reservation messages. Static priorities between ATM service classes (CBR>VBR>ABR>UBR) and the earliest due date strategy [8] within each class are employed. The scenario and source models are according to [9].

Fig. 4 shows the mean queueing delay over the frame length l_f. The delays for $l_f = 1$ are corresponding to an ATM multiplexer, where the reason for queueing delay is high traffic. The mean delay is rising with longer frames, since incoming ATM cells are not treated by their urgency till the beginning of the next frame. After that, they are scheduled by their exact urgency as in normal ATM multiplexers.

Since the considered video codex of VBR sources is generating ATM cells for one image simultaneously corresponding to a stack arrival process, all arriving VBR cells have to wait a mean time of half a frame length before they are able to be scheduled. After this time there will be enough capacity to transmit these VBR cells immediately as CBR normally requires low bandwidth and ABR has a lower priority. Thus, the mean delay of VBR sources increases half the frame length related to the ATM multiplexer $l_f = 1$ (cf. Fig. 4).

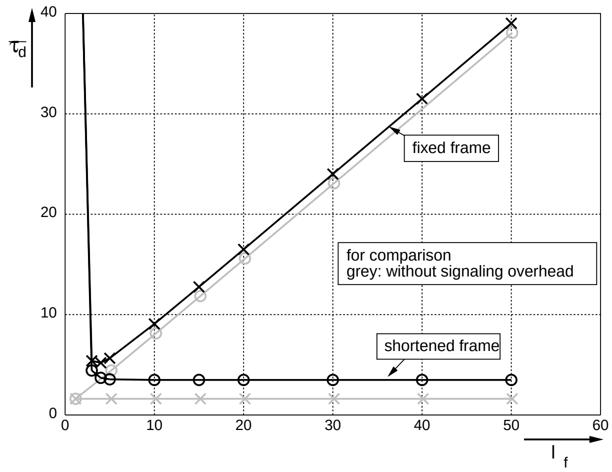

Figure 5: Mean delay for fixed and shortened frames

The delay of ABR sources is much harder to analyse, since it is not only influenced by the frame length but also by the traffic of higher prioritized service classes.

Incompletely filled up frames, resulting from not enough ATM cells waiting for transmission, should be shortened in order to advance the next frame. Fig. 5 shows the resulting considerably reduction of delays for a 50% ABR load scenario. Furthermore, the curves illustrate the influence of the signaling overhead on delays.

The negative influence of long frames becomes more critical, if messages have to be retransmitted in consecutive frames. This is necessary, especially when performing random access or repetition based error control.

3.3 Combination of vertical and horizontal reservation

Vertical and horizontal reservation can be combined utilizing the advantages of both. The part of the data rate guaranteed for most of the frames (e.g. 95%) should be reserved vertically. The other part can be reserved horizontally reacting on short term requirements.
Now the requirement of vertical reservation on a fixed frame length is no longer necessary, but still reasonable. With shortened frames vertical reservation no longer corresponds to circuit switched STDM schemes, but offers a somewhat varying capacity per channel depending on the number of horizontal slots in each frame which depends on the instantaneous capacity requirements.
The efficiency of this scheme depends on the burstiness of the sources. Only if the loss of capacity caused by unused vertical reservations is lower than the gain in saved signaling messages, this scheme can offer a good efficiency. Compared to pure horizontal reservation it will always produce longer delays for real-time oriented services, since the ATM cell scheduler is prevented from executing an optimal service strategy. Furthermore, the combination of both capacity allocation schemes leads to more complex and unreliable protocols, so that a possibly gain in efficiency must be weighed up with the disadvantages of a more complex air interface.

4 Considerations on slot types

An important goal of each protocol design is the efficient use of the available channel capacity. In this section a possible improvement is described, the usability of which depends on the offered features of the modem.
In general, there are different types of MAC messages to be transmitted, each of them with a certain length. In the slot allocation scheme with pure horizontal reservation as proposed by [6, 7, 11], there are usually four different types of MAC protocol data units (PDU) (cf. Fig. 6).

Sig-PDU (downlink) Signaling of reservation messages for the next frame, but also other control information e.g. for controlling random access or acknowledgements are possible; should have the same length as an ATM-Cell-PDU; only used on downlink.

ATM-Cell-PDU (downlink) One ATM cell with an additional MAC/LLC header with an overall length of about 55 byte; only used on downlink.

Sig-PDU (uplink) MAC/LLC signaling message like capacity request or acknowledgement with a length of about 3 byte; only used on uplink.

ATM-Cell-PDU (uplink) One ATM cell with an additional MAC/LLC header and a capacity request message with an overall length of about 57 byte; only used on uplink.

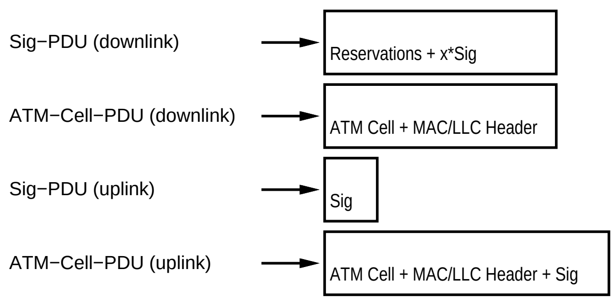

Figure 6: Different slot types

After each burst transmitted in an uplink slot a guard interval is required, the length of which depends on the radius of a radio cell. At the beginning/end of each burst an additional interval is required to control the signal power of the modem (raise/fall time).
In section 3 we assumed a slot length able to carry one ATM cell with some necessary signaling and modem overhead. This is useful, since the order of the ATM cells is determined by the ATM cells scheduler depending on their urgency. But if several uplink slots within one frame are assigned to the same WT, the modem overhead between two slots can be reduced, if these slots are neighboured (requiring reordering of slots within a frame), since the overhead for guard interval and raise/fall time between two slots belonging to the same WT could be skipped (cf. Fig. 7).

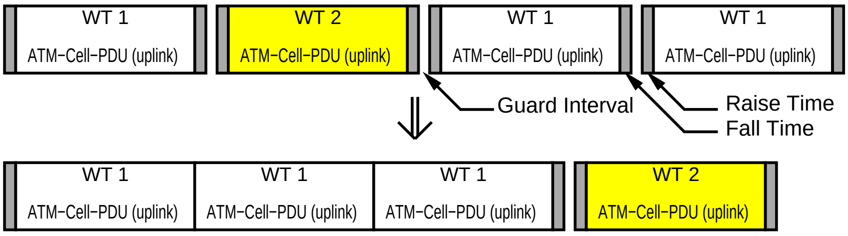

Figure 7: Combining neighboured slots belonging to the same WT

It depends on the scheduler and the type of the VCC if a reordering is possible. For example, CBR sources can be predicted very easily [8] and the scheduler is able to insert a slot for a certain time. If this slot is moved to an early time, the ATM cell might not yet been arrived at the WT and the slot would be unused.

5 Conclusions

The protocol stack of a WATM system is currently under investigation in several European ACTS projects (WAND, MEDIAN, SAMBA, AWACS, etc.) as well as national (e.g. ATMmobil founded by the German Federal Minister of Education, Science, Research and Technology (BMBF)) and industrial research projects. These projects are especially focusing on the assembly of WATM system demonstrators. The companies involved in this research work are busy in delivering input to the standardization process at ETSI RES10 and ATM Forum. First technical standards are expected to be available at the end of 1997.

6 References

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