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Performance Evaluation of a Logical Link Control Protocol for an ATM air interface

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Abstract — **The paper deals with error control procedures based on repetitions necessary for an ATM air interface, which enables a full integration of wireless (W) ATM terminals into a fixed ATM network. The architecture and functionality of an additional LLC layer at the air interface are explained. A set of ARQ protocols for the different ATM service classes is investigated. The protocol for VBR services is able to control the number of retransmissions depending on the requirements on maximum delay and residual cell loss ratio. It also takes into account the instantaneous conditions like channel load from other sources. Furthermore, the protocol is able to discard ATM cells to avoid and resolve congestion. The performance of the protocol has been evaluated by simulations.**

I. INTRODUCTION

After the success of the *asynchronous transfer mode* (ATM) in the area of multimedia networks, a demand for the transparent integration of wireless (W) ATM terminals into fixed ATM networks has become visible during the last years [1]. In 1995 ATM-Forum and ETSI have established special *W-ATM groups* that are currently investigating requirements and architectures for a wireless extension of ATM networks. In general, the users of W-ATM terminals request the same functionality and *Quality of Service* (QoS) as users of wired terminals. In Fig. 1 it is illustrated how these user requirements can be transformed into the demand on building a distributed (virtual) ATM multiplexer *around* the air interface which is characterized by a radio channel inside.

At the air interface an additional protocol stack is necessary. It contains a wireless physical layer below the ATM layer and a data link layer consisting of a *medium access control* (MAC) and a *logical link control* (LLC) sublayer which belongs to the lower part of the ATM layer.

The MAC layer is responsible for multiplexing the ATM cells of all VCs on the radio resources. Especially it has to coordinate the access to the shared radio channel in the specific scenario which is characterized by the competition of not easy to co-ordinate wireless terminals. Statistical multiplexing on a TDMA channel is used with a slot length τ_{slot} able to carry one ARQ frame[1] consisting of one ATM cell and one acknowledgement together with the necessary overhead of the physical layer for synchronization, FEC, guard time, etc. [1].

The virtual ATM multiplexer of a radio cell can be modelled as a distributed queueing system. As in normal ATM multiplexers with low data rates (e.g. 20 Mbit/s per carrier [2]) the observance of the negotiated QoS for each VC is only possible, if an ATM cell scheduler based on static or dynamic priorities is employed. The scheduler is located inside the base station. To ensure the correct execution of a service strategy, the scheduler has to be informed frequently about the status of the buffers inside the wireless terminals which is performed by transmitting capacity request messages over the uplink [3].

Based on these capacity requests, the scheduler executes a service strategy to determine for each slot the terminal which should transmit or receive an ATM cell. Static priorities are used between ATM service classes (CBR $>$ VBR $>$ ABR $>$ UBR). Within the CBR and VBR classes the *relative urgency* discipline [4] is considered, where the priorities of ATM cells depend on their waiting time and their connection specific QoS requirements. Under this strategy, the probability for cells being late (exceeding their due-dates) is minimized. The scheduling of ABR cells is based on a weighted fair queueing strategy and may be combined with the execution of ABR flow control.

The LLC layer has to perform all those standard ATM functionalities which are related to a specified virtual channel (VC), and which have to be adapted to the specific conditions of the air interface, like usage parameter control (UPC,

[1] Protocol data unit of an ARQ protocol

e.g. policing functions) [2] or ABR flow control.

The transmission over a radio link is far more unreliable than in coaxial or fiber optic cables and strongly depends on the environmental conditions. Therefore, an additional error correction scheme adapted to the characteristics of the air interface is required. This scheme consists of a hybrid combination of *forward error correction* (FEC) and *automatic repeat request* (ARQ). The FEC is included in an appropriate channel coding under responsibility of the physical layer. The ARQ protocol is executed by the LLC layer.

II. ERROR CONTROL BY AUTOMATIC REPEAT REQUEST

In our paper we focus on repetition based error control procedures performed inside the LLC layer. An ARQ protocol is able to reduce the *cell loss ratio* (CLR) but increases the cell delay τ_d by retransmissions. In the application considered, it might be not useful or even not possible to achieve a CLR on the radio link comparable to that of coaxial or fiber optic cables. Instead, the effort devoted to error correction has to be correlated to the QoS requirements of the ATM service class and can additionally be adapted for each VC. The QoS parameters to be considered are the *maximum cell delay* τ_{dmax} and the CLR.

Different ARQ protocols are required for different service classes due to their different QoS requirements. For ABR services delay is of minor interest but the residual cell loss rate should be as low as possible. This can be achieved by conventional *Go-Back-N* or *Selective-Repeat* (SR) ARQ protocols which are well investigated in literature [5].

For time bounded services like CBR and real-time VBR the delay resulting from retransmissions may become critical. Therefore, adaptive protocols are necessary which adapt the number of retransmissions to the delay of cells, and automatically adapt to the required residual cell loss ratio of a VC. So we developed special ARQ protocols for CBR (cf. Section II.D) and VBR services.

A. Selective reject ARQ protocol with discarding for VBR services

For VBR services we developed the Selective-Reject-with-Discarding (SR/D) ARQ protocol [6] that retransmits ATM cells as long as a service specific maximum delay is not exceeded. When exceeding its due-date, an ATM cell may be discarded.

The actual number of retransmissions of an ATM cell results from its priority assigned by the ATM cell scheduler in the MAC layer as well as the current channel load. The scheduling algorithm favours retransmissions, since a priority is determined considering the due-date of each ATM cell. Therefore, the increased cell delays are less resulting from multiple retransmissions of single cells, but more from the additional load caused by unsuccessful transmitted frames.

Especially for VBR services, discarding old ATM cells contributes to avoid and resolve congestion events, since the delay of the following cells can be shortened and the probability to exceed further due-dates is reduced. Therefore, special procedures have been developed (cf. Section II.C) in order to allow discarding ATM cells within an ARQ protocol which has been designed for no losses at all.

B. Transmission of Acknowledgements

The usage of a deadline oriented service strategy in the scheduler requires the generation of one ARQ instance per VC or virtual path (VP). This enables those ATM cells not belonging to the same VC to pass each other, so that it is possible to handle VCs with different priorities. An ARQ instance contains the sending and resequencing buffers.

Although virtual connections are bidirectional most of them will have unidirectional traffic flow only. In these cases there is no ATM traffic in the backward direction to carry piggybacked acknowledgements. On the other hand most of the time wireless terminals have parallel VCs and therefore parallel ARQ instances. With these parallel instances it may happen that the instance with the most urgent ATM cell does not also have to transmit the acknowledgement with the highest urgency. Hence, the information and acknowledgement fields of an ARQ frame can be occupied by different instances as long as both instances belong to the same wireless terminal. The two instances allowed to deliver the contents of an ARQ frame are determined by the ATM cell scheduler of the MAC layer. This requires two addresses inside the ARQ frame which is different from conventional ARQ protocols.

[2] In fixed ATM networks UPC is usually executed at the user terminal side of an ATM multiplexer which corresponds to the air interface protocol stack inside of the wireless terminal. But since it is not useful that a terminal is controlled by itself, a distributed algorithm is necessary with slave instances inside the wireless terminals and a controlling master instance located inside the base station.

So far, only a scheduler for the transmission order of ATM cells has been considered, the priorities of which only depend on the requirements of the source of ATM cells. As a consequence of the separation of information and acknowledgement fields, a second scheduler is necessary, determining the transmission order of acknowledgements. However, the urgency of an acknowledgement is not only given by the originator of an acknowledgement (the receiver of ATM cells), but also by the sender of ATM cells.

Positive acknowledgements are required to shift the transmission window inside the sender. Thus, the need to transmit a positive acknowledgement is always known by the sender, but usually also by the receiver by counting the number of unacknowledged information (I) frames[3]. The receiver lacks this knowledge if an acknowledgement gets lost. Negative acknowledgements are needed to request retransmissions of unsuccessfully transmitted I frames. Therefore, the need to transmit a negative acknowledgement is only known by the receiver. The explicit transmission of an acknowledgement becomes necessary, if the window of the ARQ protocol has been closed, so that no further I frames are allowed to be transmitted. If the receiver is not aware of the need to transmit an acknowledgement, even conventional ARQ protocols offer the possibility to request an acknowledgement by means of a poll bit.

For the scheduling of ARQ frames containing an acknowledgement it has to be taken into account that some MAC protocols for W-ATM systems offer the possibility to transmit short ARQ frames only containing an acknowledgement (supervisory frames) on both, downlink and uplink [7]. Transmission of acknowledgements on the uplink can be scheduled as follows, cf. Fig. 2:

1. A wireless terminal realizes the need to transmit an acknowledgement:
   (a) By increasing the priority of its ATM cells, it requests the transmission of an ATM cell piggybacking the acknowledgement. The respective capacity requirement has to be signaled to the base station.
   (b) By increasing a specific acknowledgement priority, the MAC layer is stimulated to transmit an acknowledgement in a dedicated short random access slot [3].
2. A base station realizes the need to receive an acknowledgement:
   (a) It sends an ARQ frame (with or without ATM cell) with the poll bit set in order to force the terminal to send an acknowledgement (by one of the methods described under 1).
   (b) By increasing the ATM cell priority of the terminal within the uplink scheduler, it stimulates the reservation of an uplink slot to enable the piggybacked transmission of the acknowledgement.
   (c) By increasing the acknowledgement priority of the terminal within the uplink scheduler, the insertion of a short slot into the slot sequence of the uplink is stimulated. Hereby, the transmission of the acknowledgement in a supervisory frame is enabled.

The methods 1a and 2a correspond to conventional ARQ protocols. The methods 1b and 2c can only be used if the MAC layer offers a possibility for the transmission of short supervisory frames on the uplink [7]. This allows an efficient acknowledgement of urgent ATM cells even in situations when no ATM cell of the backward direction is available to piggyback the acknowledgement.

If the need to transmit an acknowledgement has been realized in the wireless terminal as well as in the base station, the methods 2b and 2c promise the smallest overhead and the lowest signaling effort. In some special cases the other methods can also be efficient, e.g. for VCs with symmetric traffic and high data rates.

The transmission of acknowledgements over the downlink is much easier to control, because the base station defines the timing of the slot sequence. Thus, it is able to insert short slots for supervisory frames or to combine several acknowledgements into a single block which is sent in broadcast mode. If this block is not filled up by acknowledgements, further signaling messages like reservations or paging are able to be included. Within the downlink scheduler the need to transmit acknowledgements is answered by increasing an acknowledgement priority.

Another feature that can be used to reduce signaling effort and delays is the knowledge of the base station about the terminal which is allowed to transmit an I frame in a specified uplink slot. If the transmission fails, the base station may send a negative acknowledgement to the terminal. However, the base station only has knowledge of the terminal, but not of the ARQ instance which delivered the lost frame. Therefore, the acknowledging procedure is performed within the MAC layer by transmitting a feedback message comparable to the one used for announcing the result of a random access. Inside the terminal the feedback message is assigned to the right ARQ instance and converted to a negative acknowledgement [7].

[3] ARQ frames carrying an ATM cell are called information frames

The impact of separating the acknowledgement field from the information field of an ARQ frame on the link performance has been evaluated by computer simulations using the simulation model of section III. Fig. 3 shows the resulting cell delay τ_s when using different parallel ARQ instances for supervising the acknowledgement and information fields of the same ARQ frame. The simulation scenario consists of one wireless terminal operating four parallel, bidirectional VCs with asymmetric traffic load each; two VCs are driven by Poisson sources and use 30% and 10% of the channel capacity on uplink and downlink respectively, the other two VCs have the same load but in opposite direction. The overall load on uplink and downlink sums up to 80% of the channel capacity. Fig. 3 shows that with acknowledgements fixed to ATM cells, the channel is strongly overloaded. Delays are coming close to the maximum delay $\tau_{dmax} = 200\ \tau_{slot}$ (4 ms at 20 Mbit/s), and 11% of the cells have to be discarded in order to meet τ_{dmax} (cf. Section II.C). Separation of the acknowledgement field from the information field leads to a drastic improvement of the link performance illustrated by the complementary distribution function of τ_d.

C. Discarding ATM cells

With conventional ARQ protocols, after the assignment of a sequence number to an ATM cell, discarding the ATM cell will result in a protocol failure. The SR/D-ARQ protocol has been extended to be stable even with discarding of ATM cells. Three different procedures can be applied:

1. An ATM cell may be discarded, before sending it the first time (assigning a sequence number to it).
2. An ATM cell being assigned a sequence number may be discarded if the receiver is informed by an explicit discard acknowledgement.
3. The buffering of successfully transmitted ATM cells in the resequencing buffer at the receiver waiting for retransmission of lost cells with lower sequence numbers can prematurely be ended to deliver the correctly received ATM cells just in time. When the delayed cell is received correctly later, it has to be discarded. To be able to prematurely end the buffering of received cells, the knowledge of the due-date (or ages) of the buffered ATM cells is required which has to be transmitted together with the cells.

The mechanism for discarding I frames, which have been requested for retransmission (rejected by the receiver), is illustrated in Fig. 4. If the receiver requests the retransmission of an I frame (by sending a selective reject acknowledgement, SREJ), the ATM cell of which has been discarded in the meantime, the sender is not able to answer with the appropriate retransmission. To avoid a deadlock situation, the sender informs the receiver about the discarding by sending a short DISCARD message that contains the sequence number of the discarded ATM cell. The DISCARD message has the same size as an acknowledgement and thus is able to be piggybacked to an I frame.

To demonstrate the contribution of different discard procedures to the cell delay τ_d, a simulation scenario with six wireless terminals each operating one VC with symmetric traffic load driven by Poisson source has been investigated. The overall traffic load sums up to 95% which is a too heavy load for the radio link. This heavy load scenario can be viewed as representative for some “busy seconds” during a time interval with much smaller average load. The curves shown in Fig. 5 correspond to the cell discard procedures described in Table 1. The table furthermore contains the percentage of discarded and lost cells which makes the various contributions of the procedures transparent.

Without discarding any ATM cells τ_d of 90% of the cells exceed $\tau_{dmax} = 200\ \tau_{slot}$. The more cells are discarded, the shorter is τ_d of the successful cells. If cells having exceeded τ_{dmax} are counted to be lost, the cell loss rate decreases with increasing complexity of the used combination of discard procedures. Only when performing all procedures 1. to 3. together, the strict observance of τ_{dmax} is guaranteed.

D. ARQ protocol for CBR services

A special ARQ protocol for low-rate CBR services ($\tau_{dmax} < \lambda^{-1}$) is useful which is able to make use of the deterministic behaviour of the inter-arrival time λ^{-1} of CBR cells. If ATM cells are discarded automatically within a time interval which is shorter than λ^{-1}, sequence numbers are no longer necessary. In this case, the window size is reduced to one, i.e. there is no transmission window any more.

After transmitting an ATM cell over the downlink, the base station polls for an acknowledgement by inserting a dedicated short slot. Receiving a negative acknowledgement, this procedure may be repeated several times. If repetition is not continued because the ATM cell has been discarded, the terminal does not have to be informed. The transmission of ATM cells over the uplink is performed by polling which may be repeated in case of unsuccessful transmissions. By abandoning this procedure, the terminal will discard the ATM cell after a certain time. Therefore, an acknowledgement procedure for ATM cells transmitted over the uplink is not necessary.

The performance evaluation of this protocol is subject of further investigations.

III. Simulation model for performance evaluation

The performance of the presented protocols and algorithms has been evaluated by computer simulations. The scenario considered is a model of a central base station and n wireless terminals. Bit errors are generated by a two-state Gilbert model with a mean length of error bursts of $50\ \tau_{slot}$, no errors in the "good" state, a bit error rate in the "bad" state of 10^{-3}, and a mean bit error rate of 10^{-4} [1].

To determine the contributions of the various elements of the protocol, the influence of a concrete MAC protocol has been eliminated by modelling the MAC layer by a G/D/1/FCFS/RU-NONPRE model. The scheduler has an ideal knowledge of the actual capacity requirements of the wireless terminals. Acknowledgements are transmitted piggyback to information frames, and empty information frames are used to deliver acknowledgements, if requested. Because of the idealized model of the MAC layer, the delays determined by simulations can be considered a lower bound. But for the relative comparison of protocol elements on the performance, it is sufficient to compare the delay distributions achieved.

Taking into account the short round trip delay of the idealized MAC protocol, the modulus of the sequence numbers used by the ARQ instances has been set to 8 and the window size to 4.

For VBR VCs a video telephony source is modelled by an autoregressive process with a mean arrival rate amounting to 15% of the channel capacity and a period length of $1667\ \tau_{slot}$ (33 ms at 20 Mbit/s). The Poisson source is used for modelling CBR (low data rate[4]) and VBR VCs (high data rate) with QoS requirements according to $\tau_{dmax} = 200\ \tau_{slot}$ (4 ms at 20 Mbit/s). The Poisson source is used also for ABR VCs with no maximum delay requirements.

The length of a simulation run is automatically controlled by the LRE algorithm [8] which limits the relative error to a predetermined value, and which is able to handle correlations in the measured values. The relative error of the diagrams presented in this paper is always lower than 1%.

IV. Conclusions

In this paper the demands for an additional repetition based error control procedure at an ATM air interface have been described. The different requirements of ATM service classes require specific ARQ protocols adapted to the behaviour of the services. For VBR, the SR/D-ARQ protocol has been presented which employs discarding of ATM cells as well as adaption of the number of retransmission to the delay requirements and the instantaneous channel load. For CBR, an ARQ protocol has been introduced that makes use of the deterministic behaviour of the inter-arrival time of CBR cells and reduces the signaling overhead considerably. The performance evaluation of the proposed protocols has shown that the unreliable behaviour of the radio channel can be balanced by a sophisticated error control.

V. Acknowledgements

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VI. References

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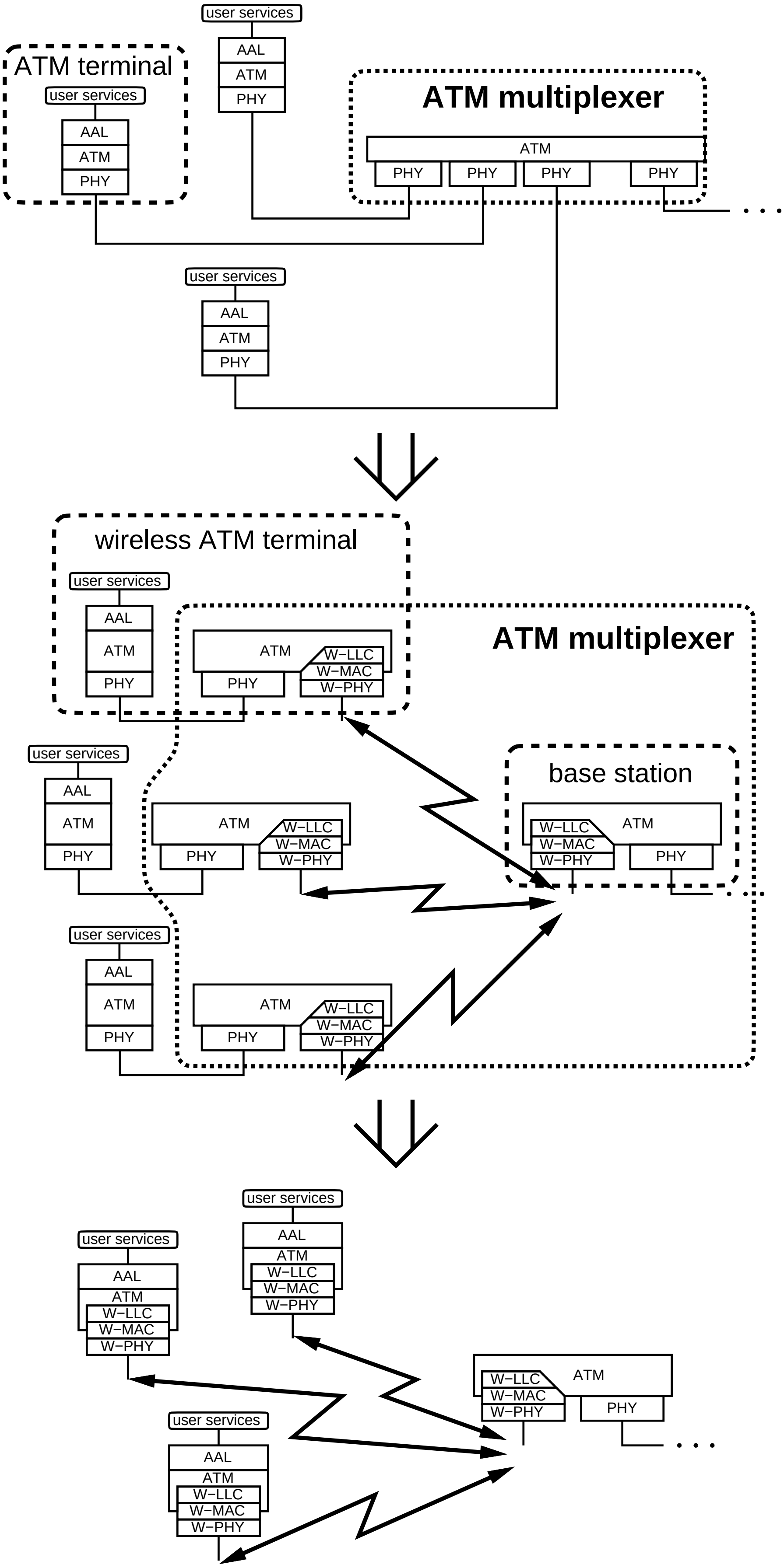
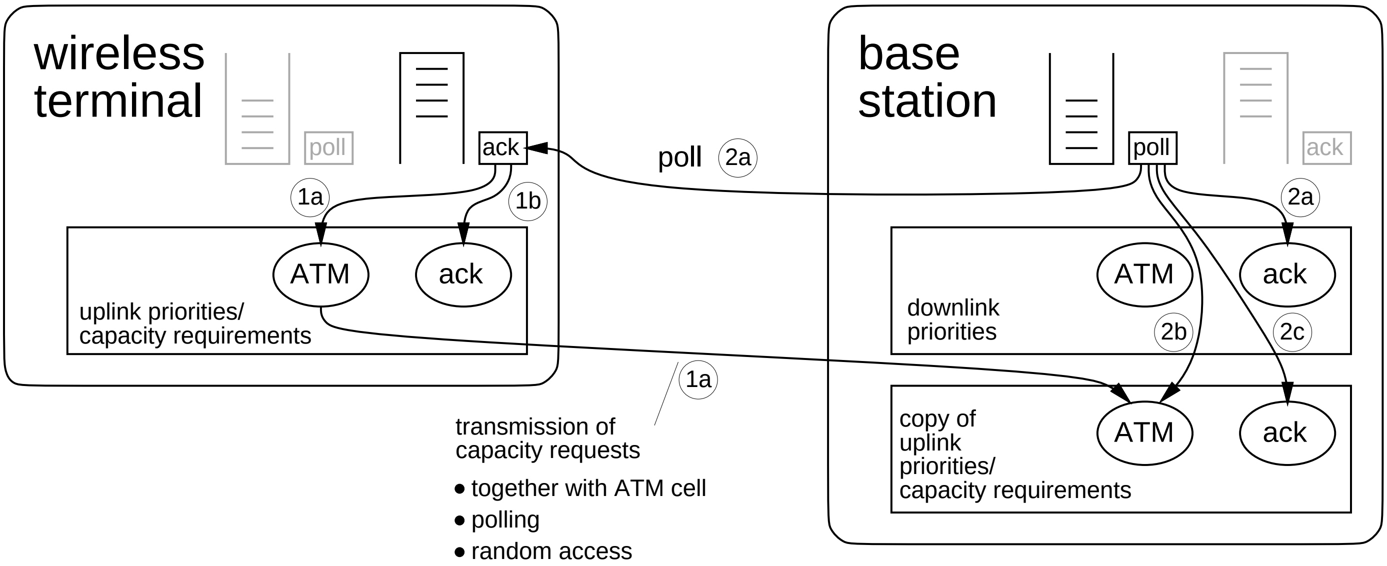
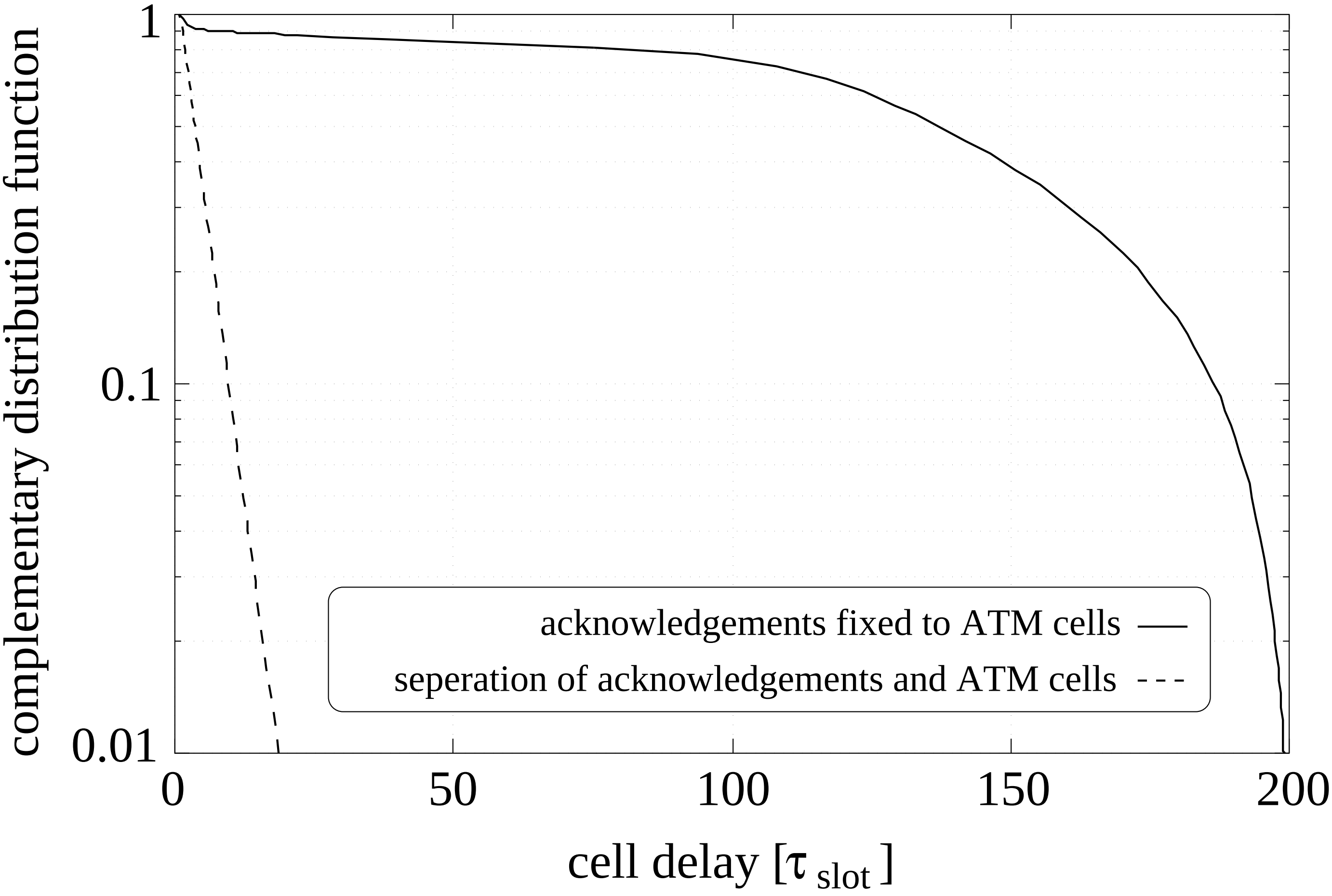
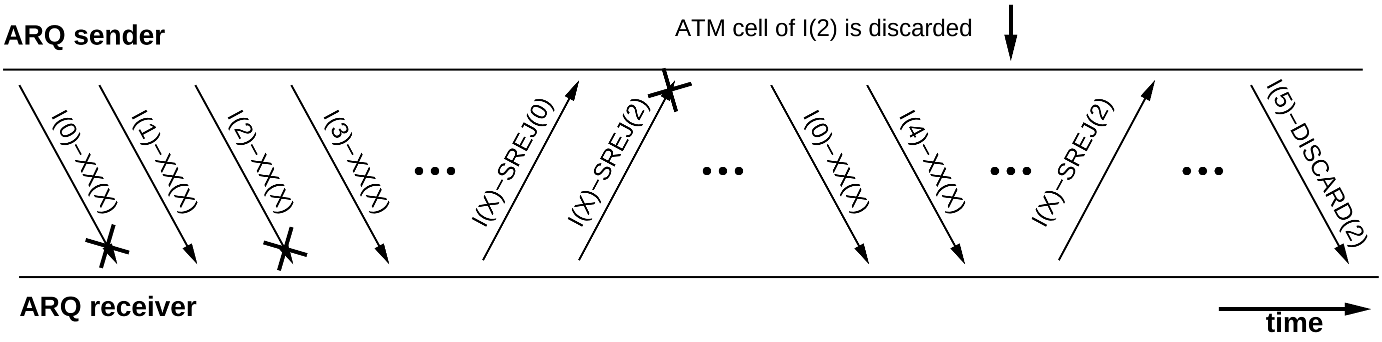


ATM terminal
user services
AAL
ATM
PHY
ATM multiplexer
ATM
PHY
PHY
PHY
PHY
wireless ATM terminal
W−LLC
W−MAC
W−PHY
base station


wireless terminal
poll
ack
1a
1b
ATM
ack
uplink priorities/
capacity requirements
poll
2a
base station
poll
ack
2a
ATM
ack
downlink priorities
2b
2c
1a
copy of uplink priorities/
capacity requirements
ATM
ack
transmission of capacity requests
• together with ATM cell
• polling
• random access


complementary distribution function
1
0.1
0.01
0
50
100
150
200
cell delay [τ slot]
acknowledgements fixed to ATM cells
seperation of acknowledgements and ATM cells



ARQ sender
ATM cell of I(2) is discarded
I(0)–XX(X)
I(1)–XX(X)
I(2)–XX(X)
I(3)–XX(X)
I(X)–SREJ(0)
I(X)–SREJ(2)
I(0)–XX(X)
I(4)–XX(X)
I(X)–SREJ(2)
I(5)–DISCARD(2)
ARQ receiver
time

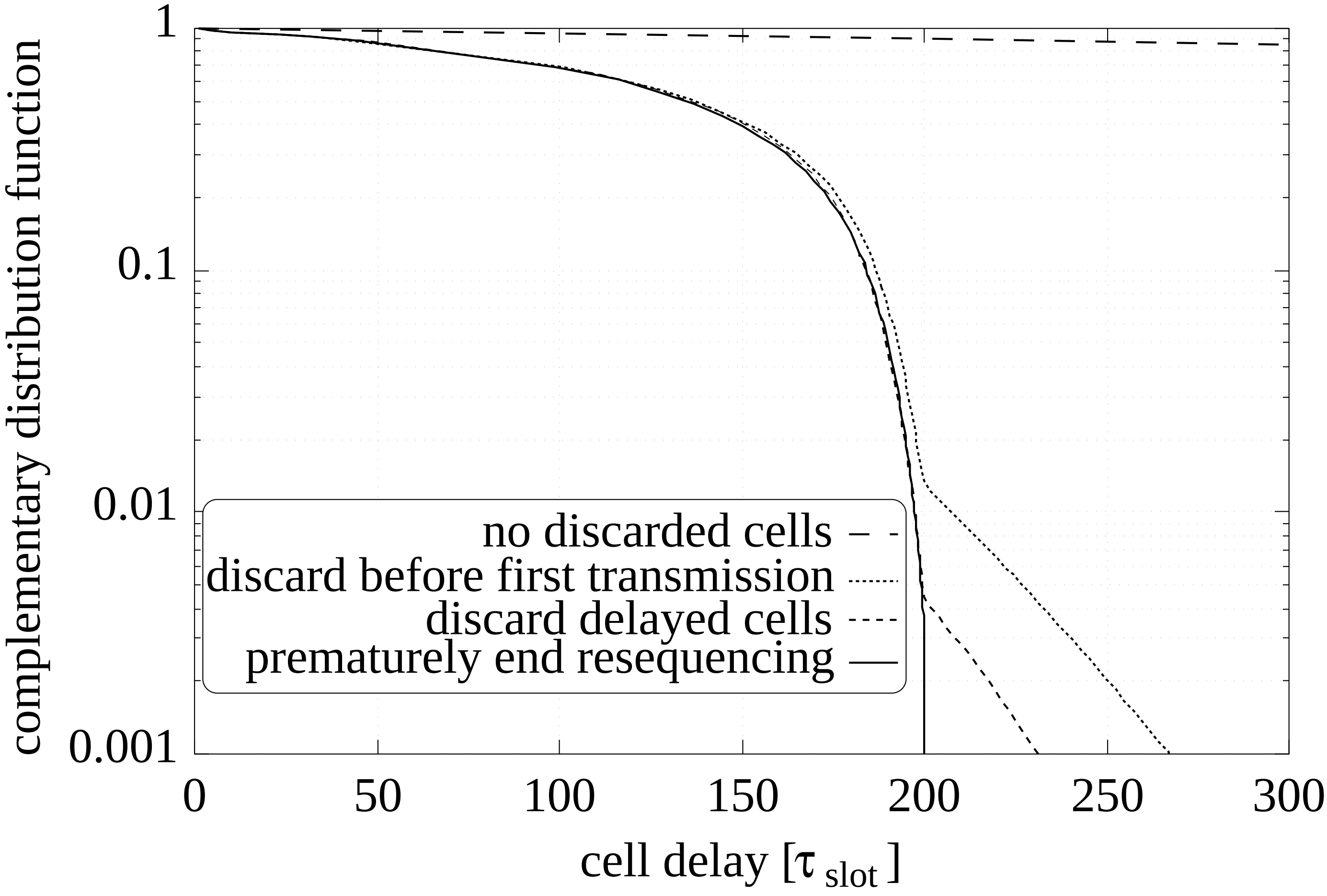

complementary distribution function
1
0.1
0.01
0.001
0
50
100
150
200
250
300
cell delay [τ slot]
no discarded cells
discard before first transmission
discard delayed cells
prematurely end resequencing

Figure 1: Correspondence between radio cell and ATM multiplexer

Figure 2: Transmission of acknowledgements over uplink and their influence on the priorities of the scheduler

Figure 3: Gain in cell delay when separating the acknowledgement field from the information field of an ARQ frame

Figure 4: Example for a protocol sequence of the SR/D-ARQ protocol with discarding information frames

Figure 5: Complementary distribution function of delay for different cell discard procedures, cf. also Table 1

Table 1: Cell discard procedures and percentage of discarded and lost cells, see Fig. 5

procedures	label in Fig. 5	% discarded cells	% lost cell
-	no discarded cells	0	90.1
1	discard before first transmission	1.85	3.07
1-2	discard delayed cells	2.31*	2.72
1-3	prematurely end resequencing	1.76*	1.76

*The number of discarded cell is smaller for prematurely end resequencing than for discard delayed cells because the transmission of the age of cells enables the usage of an optimized acknowledgement algorithm.