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wmATM ’98
1st International Workshop on Wireless Mobile ATM Implementation

April 6 thru 10, 1998. Hangzhou, China

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Joint Performance of DSA++ MAC Protocol and SR/D-ARQ Protocol for wireless ATM under realistic traffic and channel models

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Abstract — **This paper describes the protocol stack for the ATM air interface that implements the statistical multiplexing of ATM cells with a quality of service as in fixed ATM multiplexers with the same link data rate. The multiplexing is controlled by a service strategy that optimizes the resource allocation based on short-term demands of virtual channels and their negotiated quality of service. A medium access control (MAC) protocol realizes the transmission order of ATM cells given by the service strategy. By this, the protocol stack is able to efficiently support all ATM service categories. The paper focuses on a strategy for transmission of acknowledgments of an automatic repeat request (ARQ) protocol and on a collision resolution algorithm for transmission of capacity requests over the uplink. The performance of the complete protocol stack with MAC and ARQ protocols is evaluated under realistic traffic and channel models by means of an integrated stochastic simulation model.**

1. Introduction

Modern broadband multimedia telecommunication networks have to support two classes of services: synchronous services like telephony and data services like Internet. The *asynchronous transfer mode* (ATM) is able to support both classes with a unique network structure.

Wireless links are an important network element due to the high installation costs of cable-based infrastructure in the backbone and in the local loop of the user access. In cellular radio systems they furthermore enable movability or mobility of user terminals. This explains the growing demand for the transparent integration of wireless ATM (W-ATM) terminals into fixed ATM networks. Possible applications of W-ATM systems are wireless local area networks (W-ATM LAN), cellular mobile radio and radio in the local loop (RLL) networks.

In this paper we consider a W-ATM LAN corresponding to the HIPERLAN type 2 system that is currently under standardization by the ETSI-Project *Broadband Radio Access Networks* (BRAN) [1]. The system enables slow mobile wireless ATM terminals access to a fixed ATM infrastructure in a limited location area (50 m cell range). It operates on a 25 Mbps time division duplex channel in an unlicensed frequency band at 5.2 GHz.

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In general, the users at W-ATM terminals request the same functionality and quality of service (QoS) as users of wired terminals. The seamless extension of ATM to wireless terminals requires statistical multiplexing of ATM cells on the air interface. A radio cell of a W-ATM system with its terminals and the serving base station can be viewed as forming a distributed ATM multiplexer *around* the air interface which is characterized by a radio channel *inside* [2]. For the air interface an additional protocol stack is necessary. It contains a radio physical layer, with the modem below the ATM layer, and a data link control layer (DLC). The DLC consists of medium access control (MAC) and logical link control (LLC). It belongs to the ATM layer that realizes the statistical multiplexing of ATM cells.

The MAC protocol is required to coordinate the competition of terminals for the shared radio channel. The approach for the MAC protocol presented here takes into account that the performance of ATM networks is mainly influenced by the *intelligence* of the ATM cell multiplexing in ATM network nodes. Modern ATM multiplexers apply service strategies that optimize the resource allocation based on short-term demands of virtual channels (VC) and their negotiated QoS. The MAC protocol is centrally controlled by the base station and realizes the transmission order of ATM cells given by the service strategy.

This paper describes the protocol stack for the ATM air interface. It focuses on two algorithms, one for transmission of acknowledgments and one for resolution of collisions during the transmission of capacity requests over the uplink. The performance of the complete protocol stack with MAC and LLC protocols is evaluated under realistic traffic and channel models by means of an integrated stochastic simulation model.

2. MAC and LLC Protocol for the ATM Air Interface

The virtual ATM multiplexer around the air interface employs an ATM cell scheduler that executes a service strategy to determine the transmission order of ATM cells. Static priorities are used between ATM service categories (CBR > VBR > ABR > UBR). An exception are high rate CBR connections (e.g., 2 Mbps primary rate ISDN) which are served with the priority level for the VBR category. Within the CBR and VBR categories the *relative urgency* discipline [3] is considered where the priorities of ATM

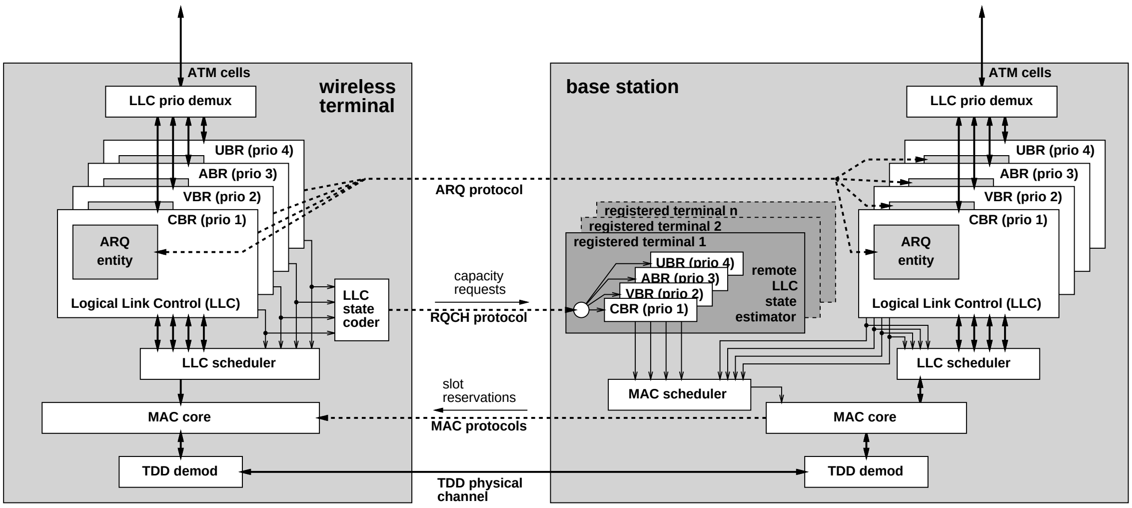

Figure 1: Structure of DLC layer with MAC and LLC scheduler.

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. For ABR services the algorithms applied for fixed ATM multiplexers are used (e.g., weighted fair queueing [4]), while the UBR service category requires fair resource sharing.

The scheduler is implemented within the DLC layer at the air interface. The following constraints have to be considered:

- The scheduler distinguishes between ATM service categories and VCs. The MAC protocol controls the access of the terminals and the base station to the shared radio channel.
- The scheduler within the base station has no direct access to the occupancy of the send buffers of the wireless terminals. A special signalling protocol is necessary in order to transmit the capacity requests of terminals to the base station.
- The unreliable behaviour of the radio channel requires additional methods for error recovery. Automatic repeat request (ARQ) protocols have to be used.
- Conventional ARQ protocols are able to transmit information (I) frames (i.e., the information field contains an ATM cell) together with piggybacked acknowledgments or short supervisory frames which contain only acknowledgments. In case of asymmetric traffic it is often impossible to transmit acknowledgments piggybacked to I-frames (ATM cells). Hence, it is necessary that the scheduler considers the transmission of ATM cells and acknowledgments.

The scheduler is divided into two parts, Figure 1. The lower part belongs to the MAC layer and decides which terminal is permitted to transmit or has to receive an ATM cell. The upper part belongs to the LLC layer. It selects the VC that is allowed to transmit or receive after the MAC scheduler has chosen the terminal.

The LLC sublayer in terminals contains an entity for each priority level of the service strategy with the send buffers of the corresponding service category. The base station contains mirrors of the terminal entities each estimating the occupancy state of the send buffers in the corresponding terminal entity. A signalling protocol (Request Channel, RQCH) is executed for notifying the mirror entities about the states of the terminal entities. This is done by generating (in the terminal) and interpreting (in the base station) capacity request messages, which are transmitted as RQCH-PDUs (ReQuest CHannel Protocol Data Unit).

The MAC scheduler uses its own send buffer states and the capacity requests of terminals, which are estimated by the mirror instances, in order to determine the reservation of slots. The terminals are notified about the slot reservations by means of a signalling protocol called *Dynamic Slot Assignment*, DSA++. It organizes the radio channel as a sequence of time slots and makes use of the four PDU types defined in Table 1.

Table 1: PDUs of the DSA++ protocol.

type	direct.	content
Period-Ctrl-PDU	down	MAC signalling, e.g., slot reservations
Down-PDU	down	ATM cell + ack.
Up-PDU	up	$n\times$ (ATM cell + ack.) + cap. request
RQCH-PDU	up	ack. + cap. request

ack.: acknowledgment
cap. request: capacity request message

For the simulations later in this paper we assume only one ATM cell per Up-PDU, $t_{\mathrm{slot}} = 20\,\mu$s for a Period-Ctrl-PDU, Down-PDU or Up-PDU and $t_{\mathrm{slot}}/4 = 5\,\mu$s for an RQCH-PDU. This corresponds to the figures currently under discussion for HIPERLAN type 2.

In order to co-ordinate the channel access, the DSA++ protocol groups slots in so-called *signalling periods*, Figure 2. During such a signalling period new capacity requests arrive at the base station and are saved in the mirror enti-

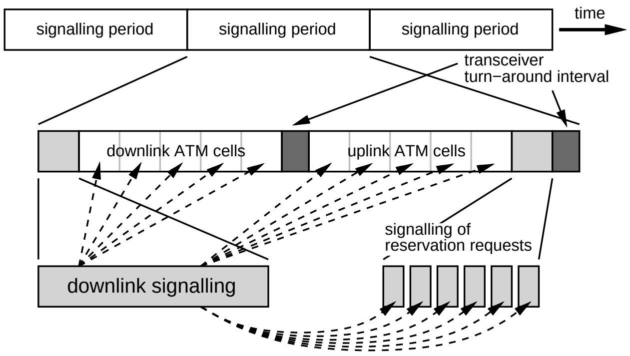

Figure 2: Signalling periods of DSA++ MAC protocol.

ties. At the end of a period the slot reservations for the next period are calculated and signalled to the terminals with a Period-Ctrl-PDU on the downlink that starts the next period. The Period-Ctrl-PDU contains the number of slots in the period and for each slot its length (number of ATM cells) and the associated terminal. A signalling period may contain a variable number of short slots for RQCH-PDUs. The access to the RQCH slots is performed with random access under control of the RQCH protocol described in section 4.

The LLC sublayer also executes the service-specific ARQ protocols. A sufficient bit error detection capability for detecting faulty ARQ frames is assumed that is combined with forward error correction (FEC) to reduce the bit error ratio of the physical channel. The ARQ instances are located at the send buffers in the entities of the LLC sublayer. The due date-based scheduling of ATM cells requires one ARQ instance per VC with real-time constraints. Acknowledgments can be transmitted piggybacked to ATM cells, capacity requests (on uplink) or Period-Ctrl-PDUs (on downlink), cf. section 3. The acknowledgment piggybacked to ATM cells may belong to a different ARQ instances than the ATM cells, since the instance with the most urgent ATM cell does not necessarily have to transmit the most urgent acknowledgment. Furthermore, it is possible to transmit several acknowledgments of one or different ARQ instances simultaneously instead of an ATM cell (bundled ack).

Two types of ARQ protocols are deployed at the ATM air interface:

Standard ARQ protocol: For ABR and UBR services no maximum delay is specified. A conventional ARQ protocol such as HDLC can be applied [5].

Real-time ARQ protocol: Real-time CBR and VBR services have high demands in meeting the maximum cell transfer delay. A *Selective Reject with Discarding*, SR/D-ARQ protocol is used that automatically discards delayed cells.

The SR/D-ARQ protocol has been described in [2] and is able to adapt the effort for error recovery to the quality of service requirements (given by the maximum delay $\tau_{d\max}$ at the air interface[1] and maximum cell loss ratio, CLR) for each VC. This adaptability is achieved by the following means:

- The number of retransmissions of an ATM cell is controlled depending on its due date (time of arrival + $\tau_{d\max}$).
- It is permitted to discard ATM cells which have exceeded their due date.

The number of retransmissions is controlled by the ATM cell scheduler. It tries to transmit an ATM cell as long as its due date has not been exceeded, which will result in the discarding of the cell. The real number of retransmissions depends on the priorities inside the scheduler as well as the current channel load. The due date-based scheduling prefers retransmissions.

Discarding of obsolete ATM cells at the air interface is advantageous in short-term congestion situations [3]. The waiting time of the following cells and the probability that further cells are exceeding their due dates are reduced.

3. Acknowledgment strategy

Cell delays and throughput highly depend on how acknowledgments are generated and transmitted. The reservation of capacity for transmission of acknowledgments is only done by the ARQ instances of the base station. The acknowledgment of uplink cells happens according to the state of the receive instances in the base station. The urgency for acknowledging downlink cells is derived from the send instances of the base station by taking into account the number and priority of unacknowledged cells.

ARQ instances generate acknowledgments in the following order:

1. Negative acknowledgment
2. Discard message[2] or positive acknowledgment as answer to polling (alternating)
3. Positive acknowledgment

The following methods for transmission of acknowledgments are available, Figure 3.

Downlink:

1. Up to 6 acknowledgments in a Period-Ctrl-PDU
2. Piggybacked to an ATM cell in a Down-PDU
3. Up to 24 acknowledgments in a Down-PDU (bundled ack)

Uplink:

4. Piggybacked to an ATM cell in an Up-PDU
5. Up to 24 acknowledgments in an Up-PDU (bundled ack)
6. In a polled (reserved) RQCH-PDU
7. In an RQCH-PDU transmitted in random access

Transmission of acknowledgments is performed by the following tasks:

[1] The ATM traffic contract specifies no maximum delay $\tau_{d\max}$ at the air interface. With the maximum transfer delay maxCTD specified in the ATM traffic contract, the assumption of $\tau_{d\max} = 0.1\,\mathrm{maxCTD}$ seems to be useful.

[2] A discard message informs the receiver that the sender has discarded an ATM cell, which the receiver is requesting for retransmission.

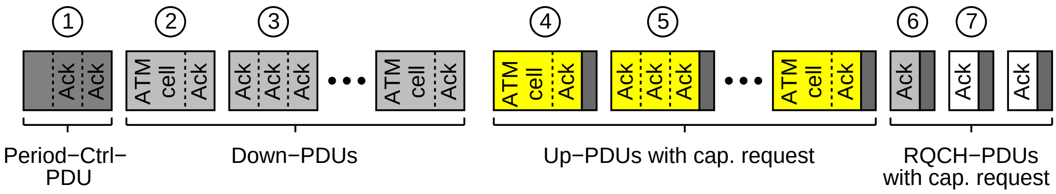

Figure 3: Signalling period with transmission of acknowledgments.

- Each Period-Ctrl-PDU transports up to 6 downlink acknowledgments. Those acknowledgments are preferred that have no corresponding ATM cells to be piggybacked in a Down-PDU
- Urgent acknowledgments increase the priority of corresponding ATM cells in order to be piggybacked in a reserved slot.
- If the base station expects an urgent acknowledgment from a terminal that has no ATM cell to transmit, it reserves a short RQCH slot to the terminal to piggyback the acknowledgment to an RQCH-PDU. If several acknowledgments are expected from the same terminal, e.g., if several VCs are operated in parallel, a slot for an Up-PDU is reserved.

If a terminal wants to transmit an urgent acknowledgment, it has to send an RQCH-PDU in a random access slot. Due to possible collisions and resulting delays this is only used in exceptional situations.

4. Signalling of capacity requests

The goal of signalling capacity requests over the uplink by means of the RQCH protocol is the sufficient information of the ATM cell scheduler in the base station about the occupancy state of the send buffers in terminals. The RQCH protocol has to solve the following requirements:

In time signalling: To guarantee the required maximum delay $\tau_{d\max}$ of real-time services the signalling of new arrivals has to be performed in time.

Small signalling effort: Signalling competes with transmission of ATM cells; channel capacity occupied by signalling leads to longer delays of ATM cells.

Sufficient coding of capacity demand: A too vague coding of the occupancy state of send buffers may lead to a waste of channel capacity if more slots are reserved than necessary. It may also increase delays if too few slots are reserved.

The RQCH protocol has to take into account the following aspects:

- Coding the occupancy state of send buffers
- Determining frequency and times of signalling events
- Transmission method of capacity requests

The procedure for coding the occupancy state is adjusted to the different service strategies (one per service category or priority level) in the ATM cell scheduler. Since the MAC protocol distinguishes between terminals whereas the scheduler distinguishes between VCs, the buffer states of all VCs in a terminal of the same priority level are combined and coded to a generic data structure of 2 byte size called *dynamic parameters*[3]. The capacity demand of a terminal is expressed by a group of dynamic parameter objects, with one object per priority level. When transmitting a capacity request, a terminal chooses the dynamic parameters of the level of highest priority with buffered cells.

VBR, high rate CBR: Since VBR cells are served by a due date-based strategy, their dynamic parameters contain the residual life time (time interval till due date, logarithmic coding) of the most urgent cell together with the number of further cells with comparable urgency.

Low rate CBR: The dynamic parameters of the CBR service category are coded analogous to VBR. An optimized procedure may use the deterministic inter-arrival time of CBR cells in order to extrapolate the arrival time of the next cell. The dynamic parameters are used to synchronize the base station on the arrival process in terminals. After a faulty extrapolation a terminal has to transmit its dynamic parameters explicitly to the base station.

ABR: The dynamic parameters of the ABR service category contain the number of buffered cells and may be used to control ABR flow control.

UBR: The dynamic parameters of the UBR service category contain the number of buffered cells.

The DSA++ protocol offers two transmission methods for dynamic parameters:

- Piggybacked to ATM cells
- With RQCH-PDUs in short slots with random access or polled by the base station

The transmission happens depending on the reservation state of a terminal. Figure 4 shows the corresponding state transition diagram. State *IDLE* corresponds to an empty send buffer so that no capacity request is to be send. After the arrival of an ATM cell the terminal changes to state *REQUEST* (transition ①) and tries to transmit its dynamic parameters in a short RQCH slot. After a successful transmission the terminal enters state *RESERVATION* (transition ②) and will be served by the scheduler according to the urgency of its ATM cells. With the transmission of an ATM cell in a reserved slot the scheduler is informed about the newest capacity demand by means of the piggybacked

[3]The name "dynamic parameters" indicates the dynamic characteristic of the capacity demands in contrast to the static traffic descriptors and QoS parameters.

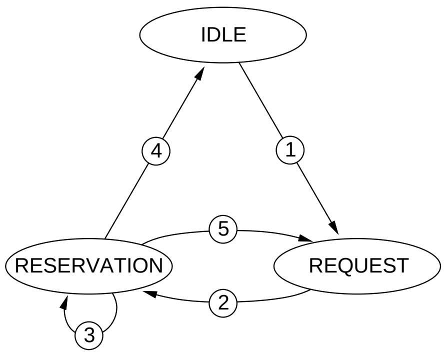

Figure 4: Reservation states of terminals.

dynamic parameters (transition ③). If no further capacity is required, no dynamic parameters are transmitted and the base station recognizes that the terminal has returned to state *IDLE* (transition ④).

A special case is the parallel existence of VCs of different service categories. If a terminal did request capacity for a low priority service category (e.g., UBR) and thus is in state *RESERVATION*, the arrival of an ATM cell of a high priority category (e.g., VBR) may modify the capacity demand such that the terminal is not able to wait for the next reserved slot in order to piggyback the newest dynamic parameters on an ATM cells. Instead it goes back to state *REQUEST* (transition ⑤) and forces the retransmission of its dynamic parameters over the RQCH.

The MAC instance in the base station tracks the reservation state of all terminals in order to estimate the number of terminals that will send in a RQCH slot for random access. By receiving dynamic parameters, the base station is able to detect the state transitions ②, ③ and ④. But it cannot detect the transitions to state *REQUEST*. Due to a corrupted transmission of dynamic parameters the base station may miss a terminal's transition to state *RESERVATION*. The terminal has to be able to detect this and to return to state *REQUEST*. For this purpose each Period-Ctrl-PDU signals the priority value of the latest scheduled ATM cell. A terminal compares this value with its own capacity demand and thus is able to realize that it has not been considered despite its sufficient high urgency. In this case it concludes on the loss of its last transmitted dynamic parameters and forces their retransmission.

5. RQCH Random Access Protocol with fast Collision Resolution

The RQCH protocol gives terminals the possibility to initiate the transmission of their dynamic parameters by themselves. Since it employs random access, a stable and fast algorithm for collision resolution is necessary. The period structure of the DSA++ protocol gives rise to following constraints for random access.

- The result in a random access slot is broadcasted to the terminals with feedback message inside the next Period-Ctrl-PDU. Thus, there is the situation with delayed feedback as described in [5].
- Each period can provide nearly any number of random access slots. The maximum number is only limited by the size of the Period-Ctrl-PDU, because it has to carry the necessary signalling messages.

Due to the urgency of the transmission of dynamic parameters, the random access is not to be optimized for throughput, but for short delays. Critical are the delayed feedbacks, since a second random access of the same terminal is only useful if the feedback of the first access has been evaluated before. Therefore, dedicated shortened signalling periods are used to enable fast transmission of feedbacks. A maximum period length of the DSA++ protocol is defined by the number of reservation messages in a Period-Ctrl-PDU. This PDU has the same length as a Down-PDUs (≈53 byte), but due to its importance for protocol stability its content is protected by a special FEC. Thus, we assume $N_{\mathrm{Res\,max}} = 20$ reservation messages per Period-Ctrl-PDU. Each reservation of a random access slot as well as each feedback message replaces a reservation message for an ATM cell slot. Thus, periods are automatically shortened with increasing number of random access slots.

Delays in random access are also influenced by the used collision resolution algorithm. The algorithm proposed in the following is a non blocking adaptive identifier splitting algorithm [5] that takes advantage of the known number of terminals in contention mode (not in state *RESERVATION*), since only registered terminals are allowed to request capacity. This algorithm has been analysed in [6], where it is called the *probing algorithm*. It uses the unique terminal identifiers that are assigned to terminals during a registration procedure.

At the beginning of each signalling period the probing algorithm divides the identifier space (of size N) into a variable number t of consecutive intervals and assigns one RQCH slot to each interval. The lth interval starts with terminal i_l and ends with terminal $i_{l+1}-1$, with $i_1 = 0$ and $i_t = N-1$. It contains $K_l = i_{l+1} - i_l$ terminals. The Period-Ctrl-PDU signals the interval division to the terminals by transmitting the start identifier i_l of each interval.

The width of each interval is determined by considering the probability $p_{\mathrm{send},i}$ that terminal i will send in an RQCH slot. For terminals in state RESERVATION $p_{\mathrm{send},i}$ is zero. For all other terminals the base station approximates $p_{\mathrm{send},i}$ by modelling the arrival process of the next ATM cell by a simple Poisson process with parameter λ_i. With this model $p_{\mathrm{send},i}$ corresponds to the probability of at least one arrival at terminal i during the interval $t_{\mathrm{slot}} - t_{\mathrm{last\,send},i}$ since the last transmission of its dynamic parameters (in an RQCH slot or piggybacked to ATM cells), with t_{slot} being the time of the considered RQCH slot,

$$p_{\mathrm{send},i} = 1 - C_i \cdot \exp\left[-\lambda_i \cdot (t_{\mathrm{slot}} - t_{\mathrm{last\,send},i})\right] \qquad (1)$$

The parameter C_i is set to 1 and will be explained later.

The width of each interval is calculated by maximizing K_l under the constraint

$$N_l = \sum_{i=i_l}^{i_{l+1}-1} p_{\text{send},i} < W \tag{2}$$

With the parameter W the probability of a successful transmission can be adjusted. The analysis in [6] has shown that $W \approx 1.4$ corresponds to binary splitting and $W \approx 0.9$ to ternary splitting. With higher splitting order, shorter delays are reached, which is paid for by a lower efficiency of random access.
At the end of a period the results of accesses are used to correct the estimation of $p_{\text{send},i}$. If no or one transmission happened in a slot (error-free feedback assumed), $t_{\text{last send},i}$ is set to t_{slot} and C_i is reset to 1 for all involved terminals. If a collision occurred in the slot belonging to the lth interval, the number $N_{\text{coll},l}$ of involved terminals is estimated by

$$N_{\text{coll},l} = N_l \frac{1-(1-N_l/K_l)^{K_l-1}}{1-(1-N_l/K_l)^{K_l} - N_l\,(1-N_l/K_l)^{K_l-1}} \tag{3}$$

The estimation is based on the assumption of a binomial distribution of N_l. This is not an exact model, but a sufficient approximation. We correct the estimation of $p_{\text{send},i}$ by adjusting C_i:

$$C = \frac{K_l - N_{\text{coll},l}}{K_l - N_l} \tag{4}$$

$$C_{i,\text{new}} = C \cdot C_{i,\text{old}} \tag{5}$$

After a successful or no transmission in a slot, C_i of the terminals in the relevant interval is reset to 1.
To guarantee limited delays, two further rules are necessary:

- After the second collision terminals are not allowed to be in the same group with uncollided terminals.
- During an ongoing collision terminals have to be included in groups with decreasing size.

The correct determination of the parameter λ_i is a difficult task since it cannot be derived from the ATM traffic descriptors. An adaptive algorithm based on traffic measurements seems to be an adequate solution but is for further study.
Finally, the extensions of the signalling scheme avoids the segmentation of the identifier space into too small groups by enabling the polling of terminals in dedicated RQCH slots and combining the groups right and left from the polled terminal (Figure 6). For this, an additional list is signalled with each Period-Ctrl-PDU that contains the terminal identifiers of polled terminals. If the probing algorithm creates a group that contains only one terminal, it polls the terminal and tries to combine the adjacent groups. Figure 5 gives an example for the distribution of terminals on groups. It shows a sequence of 16 periods for a scenario with 20 registered terminals.

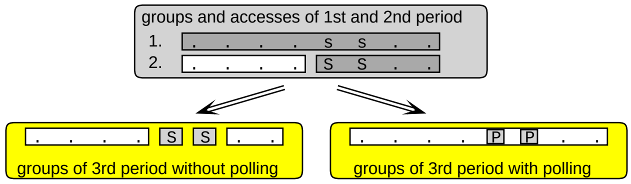

Figure 6: Example for the polling of a single terminal within a group (cf. Figure 5 for abbreviations).

6. Integrated Stochastic Simulation Model for Parametrization and Performance Evaluation of the ATM Air Interface

The performance of the protocol stack at the ATM air interface highly depends on the parameter setting of MAC and ARQ protocols. Due to the mutual dependencies between the mechanisms of SR/D-ARQ, RQCH and DSA++ protocols, partly with contrary effects, the appropriate settings can only be determined when considering the whole protocol stack under realistic environmental conditions.
The simulation model is based on an event driven stochastic computer simulation according to [7, 8].
The behaviour of the physical channel is modelled by an error-free transmission and by two error models, which provide uncorrelated random errors and correlated errors based on a Gilbert model. The parametrization of the error models considers an indoor mobile radio channel with a mean packet error ratio of 2.5% for both error models. The models correspond to extreme cases of the complex behaviour of realistic radio channels.
The protocol overhead O is defined to $O = 1 - \rho_{\text{max}}$, based on the maximum achievable throughput ρ_{max} that only considers successfully delivered ATM cells. Transmission errors are included in O in order to take into account the effects of erroneous signalling.
ρ_{max} is measured as follows: with a given traffic scenario a further terminal with a UBR connection is added that is always able to send an ATM cell and fills up all empty slots. Due to the static priorities in the scheduler this does not effect the performance of CBR and VBR services.
The length of a simulation run has been controlled by prescribing a relative error supported by the LRE algorithm [9], which considers correlations between measured values. The relative error of all presented results is lower than 5%.

7. Parametrization of Probing Algorithm in DSA++ Protocol

The optimal value for W of the probing algorithm is determined by a simulation model of the DSA++ protocol. Only error-free transmission is considered so that no ARQ protocol has to be executed. The influence of transmission errors on collision resolutions is considered later in this paper.
The simulation scenario assumes 10 terminals with one bidirectional VC each. The load is resulting from Poisson sources and is equally distributed between the VCs on

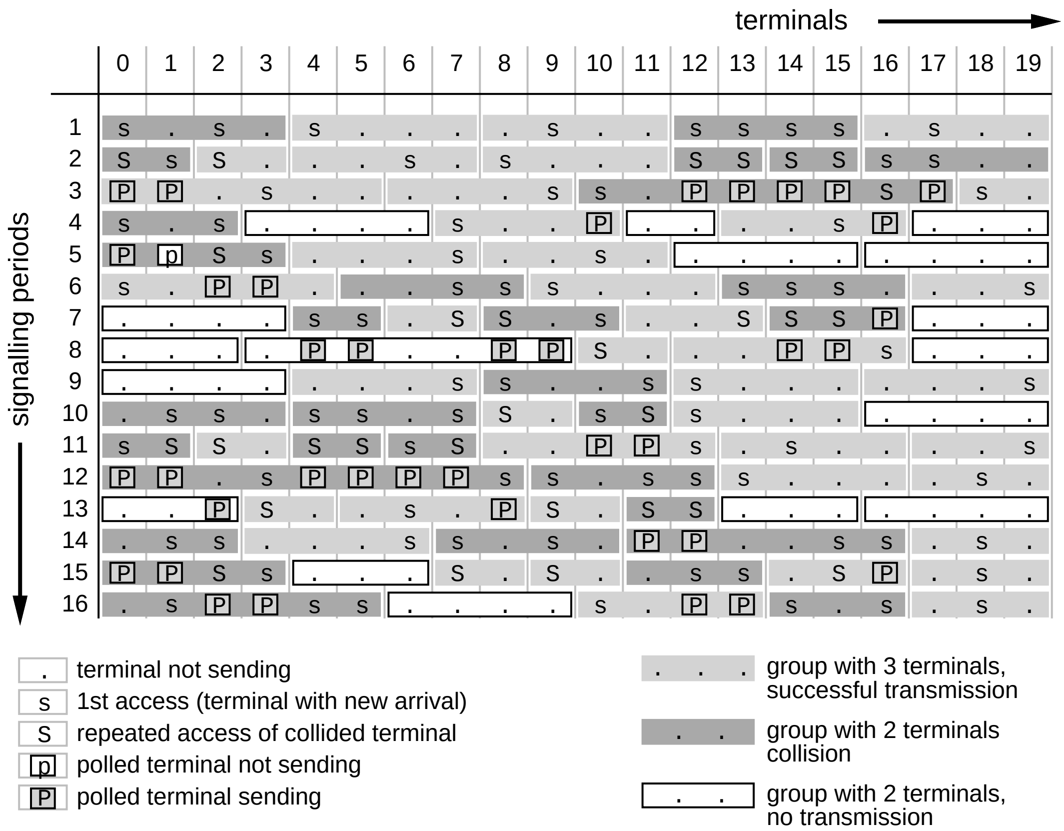

Figure 5: Example for distribution of terminals on groups with the probing algorithm for 16 periods and a scenario with 20 terminals.

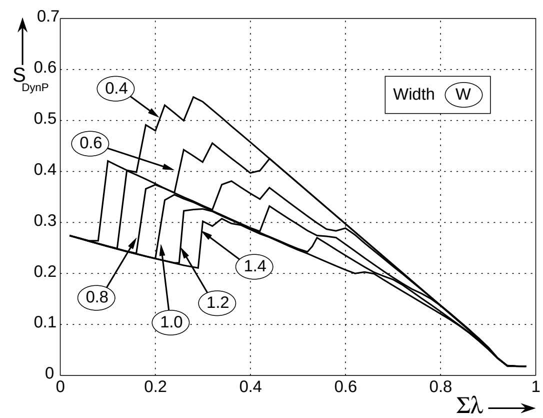

Figure 7: Signalling effort S_{DynP} of the transmission of capacity requests in RQCH slots against overall load $\sum \lambda$.

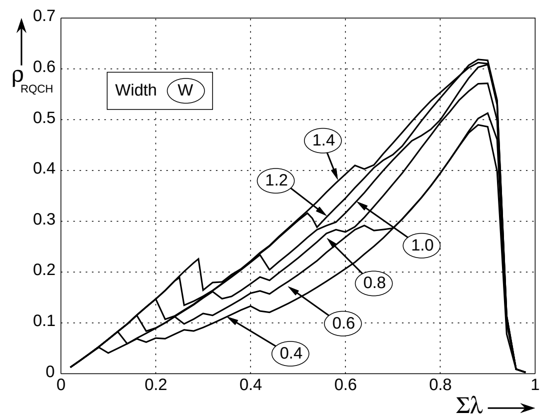

Figure 8: Efficiency ρ_{DynP} (probability of success) of the transmission of capacity requests in RQCH slots against overall load $\sum \lambda$.

uplink and downlink. The overall load $\sum \lambda$ is varied from 0 to 1. Figure 7 shows the signalling effort S_{DynP} and Figure 8 the efficiency ρ_{DynP} (probability of success) of the transmission of capacity requests over the RQCH. In Figure 9 the mean number of signalling periods $\overline{N}_P$ till a successful transmission is shown for W between 0.4 and 1.4. Figure 10 shows for $W = 1.0$ the threshold $\hat{N}_S$ of delays (measured in multiples of slot length τ_{slot}) that is exceeded by a certain fraction of capacity requests[4].

It can be seen that lower values of W lead to shorter RQCH delays but reduces the efficiency ρ_{DynP}. The faster RQCH reduces the delay of uplink ATM cells and the lower efficiency ρ_{DynP} together with the higher signalling effort

[4] The maximum delay for high load $\sum \lambda$ is limited to the maximum period length of $19.25\tau_{\mathrm{slot}}$ (19 ATM cell slots of length τ_{slot} and one RQCH slot of length $\tau_{\mathrm{slot}}/4$).

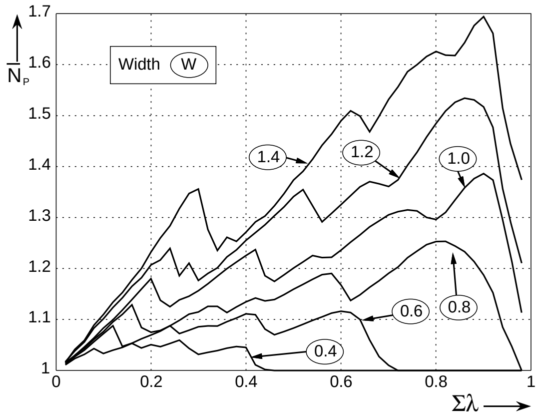

Figure 9: Mean number of signalling periods $\overline{N}_P$ till successful transmission over RQCH against overall load $\sum \lambda$.

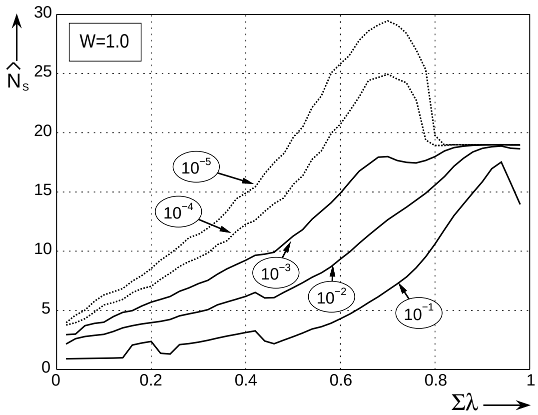

Figure 10: Threshold $\hat{N}_S$ of delays (measured in multiples of slot length $\tau_{\rm slot}$) that is exceeded by a certain fraction of capacity requests for $W = 1.0$ (dotted curves are statistically not proven).

$S_{\rm DynP}$ increases the delay of downlink ATM cells. $W = 0.8$ seems to be a good compromise between delays and efficiency.

8. Performance Evaluation of the ATM Air Interface

This section presents a detailed performance evaluation of the whole protocol stack based on the two realistic multimedia scenarios in Table 2 and 3. The scenarios consider terminals that operate one bidirectional VC of the specified service class and traffic model each.

The voice service corresponds to a 64 kbps PCM codec,

Table 2: Parameters of the 1st multimedia scenario.

Service	Category	λ	#WT	$\sum$Load	$\tau_{d\,\max}$	$\tau_{d\,\max}/\tau_{\rm slot}$
Voice	CBR	64 kbps	4	3%	2 ms	100
Video	VBR	1 Mbps	4	44%	30 ms	1500
Data	UBR	460 kbps	4	20%	Undef.	Undef.

Table 3: Parameters of the 2nd multimedia scenario.

Service	Category	λ	#WT	$\sum$Load	$\tau_{d\,\max}$	$\tau_{d\,\max}/\tau_{\rm slot}$
Voice	CBR	64 kbps	4	3%	2 ms	100
ISDN*	VBR*	2 Mbps	1	22%	5 ms	250
Video	VBR	1 Mbps	2	22%	30 ms	1500
Data	UBR	460 kbps	4	20%	Undef.	Undef.

* Primary rate ISDN connection belongs to CBR service category but is serviced with the VBR priority level of the scheduler, since the higher CBR priority level only services low rate CBR connections (e.g., 64 kbps).

Table 4: Parameter settings of protocol stack for performance evaluation.

max. No. reservations $N_{\rm Res\,max}$ in Period-Ctrl-PDU	20
max. No. acknowledgments in Period-Ctrl-PDU	6
Ratio of UP-PDU/RQCH slot length $r_{\rm slot}$	4
Group weight W of probing algorithm	0.8

the video service is according to [10], and the data service is modelled by a Poisson source.

If not otherwise mentioned, the parameter settings in Table 4 are used.

1. *Maximum number $N_{\rm Res\,max}$ of reservations in signalling period*

The maximum number of reservation messages in a Period-Ctrl-PDU for Down-PDUs, Up-PDUs and RQCH-PDUs as well as random access feedbacks is given by the parameter $N_{\rm Res\,max}$. To study the influence of $N_{\rm Res\,max}$, it is varied between 16 and 64. For simplification the dependency of $N_{\rm Res\,max}$ from the structure and size of a Period-Ctrl-PDU is neglected. To avoid the closing of ARQ windows [2], their maximum size is set to $2N_{\rm Res\,max}$.

Higher values of $N_{\rm Res\,max}$ allow longer signalling periods and lead to less frequent transmissions of Period-Ctrl-PDUs. Having in mind the above simplification, this reduces the protocol overhead O. Longer signalling periods furthermore reduce the acknowledgment traffic since the piggybacked transmission of acknowledgments becomes more probable.

The video sources cause batch arrivals which result in phases with very high load. The expected high dependency of the protocol overhead O on $N_{\rm Res\,max}$ is proven by the simulation results in Figure 11. O decreases continuously with increasing $N_{\rm Res\,max}$ with similar behaviour for the different channel models.

The results show that uncorrelated errors lead to a higher effective error ratio and thus to a higher protocol overhead than correlated errors. The reason is the loss of a Period-Ctrl-PDU, which causes that a terminal can not identify its slot reservations. With correlated errors it is very likely that the transmission in the reserved slots would have failed too. With uncorrelated errors a transmission in the reserved slots would have been possible but could not take place due to the missed reservation message. This increases the effec-

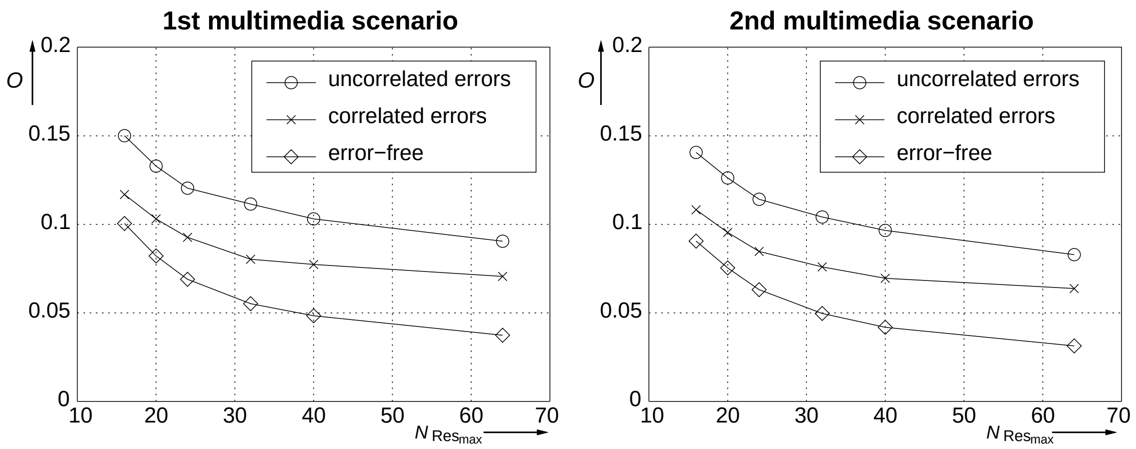

Figure 11: Protocol overhead O against maximum number of reservation messages $N_{\mathrm{Res}_{\max}}$ within the Period-Ctrl-PDU.

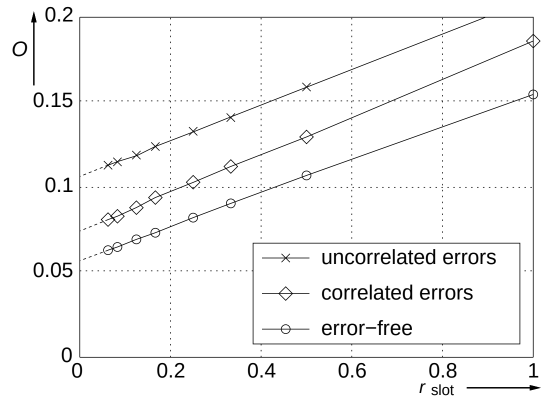

Figure 13: Protocol overhead O against ratio of RQCH to Up-PDU slot length r_{slot} for 1st multimedia scenario.

tive packet error ratio.

The resulting protocol overhead for the 2nd scenario is slightly lower than with the 1st scenario, since the 2 Mbps CBR connection allows the piggybacked transmission of all acknowledgments in contrast to the video connection, where most uplink acknowledgments are send in RQCH-PDUs.

Shorter signalling periods enhance the flexibility of protocols and shorten response times: The scheduler considers new arrivals earlier, the collision resolution is speeded up and erroneous packets are retransmitted faster. Thus, large values of $N_{\mathrm{Res}_{\max}}$ have a negative influence on transmission delays of real-time services. This mostly affects CBR connections which demand very small maximum delays. In Figure 12 the delays of up- and downlink CBR cells continuously increase with higher $N_{\mathrm{Res}_{\max}}$. The curves give rise to following conclusions:

- CBR connections are served with highest priority, so that in case of error-free transmission their downlink cell delays are caused only by the period-oriented transmission which considers new arrivals not before the next period. The maximum delay is determined by the maximum period length ($\approx N_{\mathrm{Res}_{\max}} \cdot \tau_{\mathrm{slot}}$).

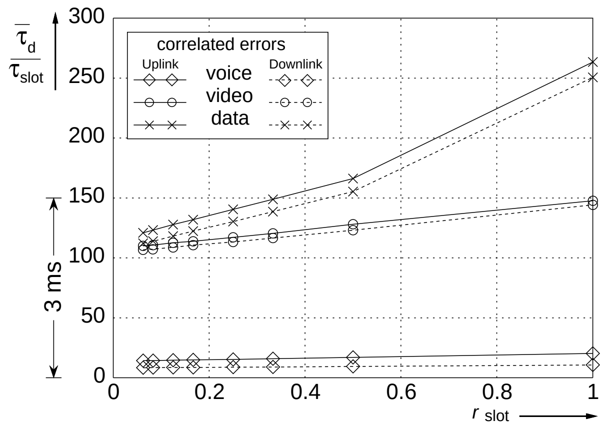

Figure 14: Mean delay $\overline{\tau}_d$ of up- and downlink (correlated transmission errors) against ratio of RQCH to Up-PDU slot length r_{slot} for 1st multimedia scenario.

- Uplink ATM cells are transmitted at the end of a signalling period. The transmission of downlink cell batches of video sources causes an additional delay of CBR uplink cells of up to one maximum period length compared to downlink CBR cells. This happens in $\approx 20\%$ of time.
- For low rate CBR connections an arriving uplink cell always encounters an empty send buffer. Thus, the terminal always has to request capacity via the RQCH which increases delays. Large values of $N_{\mathrm{Res}_{\max}}$ result in long signalling periods and cause large access delays. For $N_{\mathrm{Res}_{\max}} = 32, 40, 64$ the maximum allowed transmission delay of voice services cannot be met.
- When a transmission error of a CBR cell occurred, the retransmission will not happen before the next signalling period. During phases with high offered load (e.g., during the transmission of a video image) all signalling periods are of maximum length. With too large $N_{\mathrm{Res}_{\max}}$ retransmissions cannot be executed in time. This explains the large cell losses for $N_{\mathrm{Res}_{\max}} = 64$.

In ATM systems meeting the maximum transfer delay of

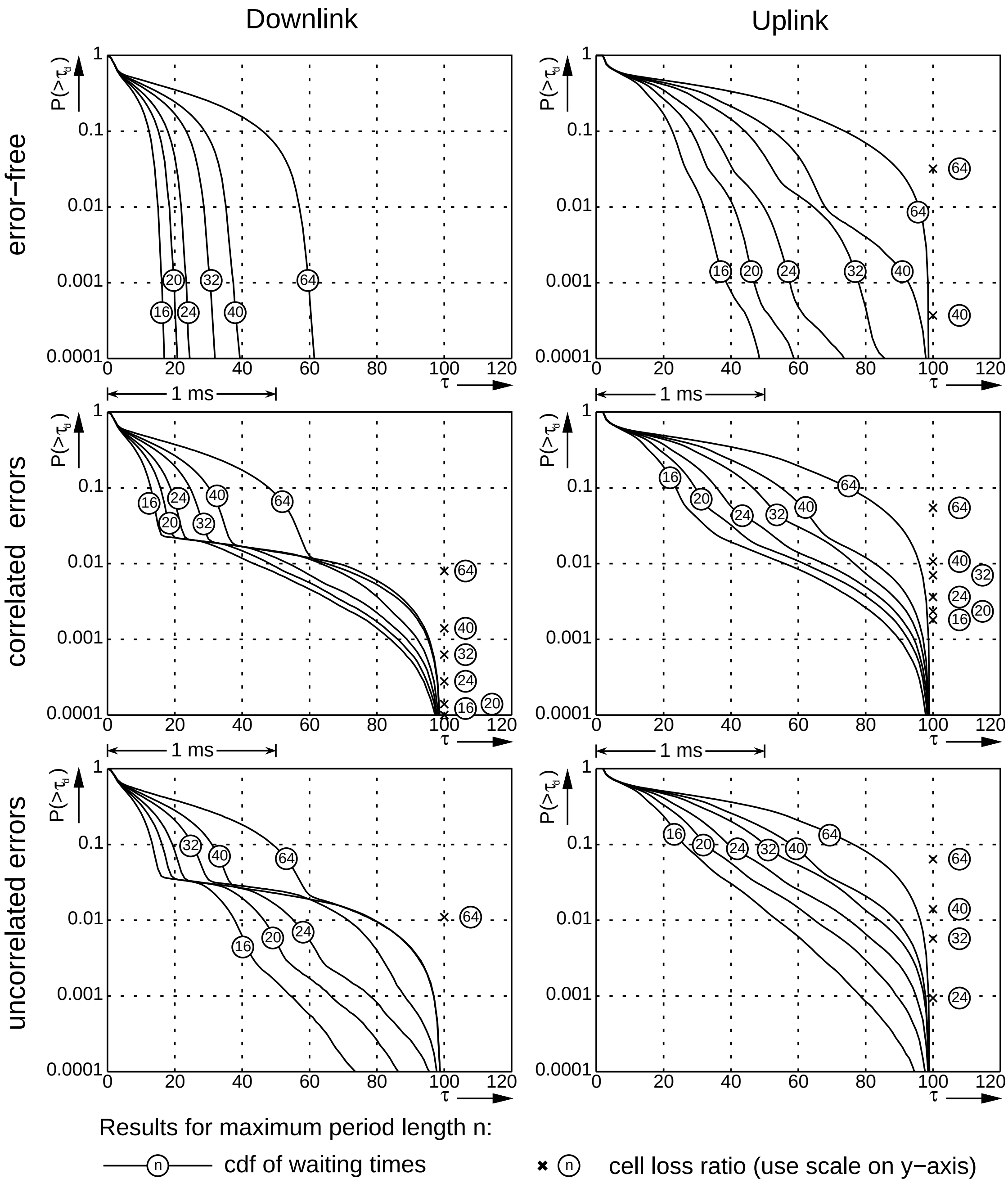

Figure 12: Complementary distribution functions (cdf) of transmission delays and cell loss ratios for the CBR connections of the 1st multimedia scenario.

ATM cells of real-time services is more important than a slightly improved channel efficiency. Thus, $N_{\mathrm{Res}\max} \leq 24$ is reasonable. Although the QoS of CBR connections could be met with $N_{\mathrm{Res}\max} = 24$, we choose $N_{\mathrm{Res}\max} \leq 20$. This provides additional space within the Period-Ctrl-PDU for messages of mobility and network management.

2. Ratio r_{slot} of RQCH to Up-PDU slot length

RQCH-PDUs only carry protocol control information (capacity requests, acknowledgments). Thus, the length of their slots directly affects the protocol overhead O. The ratio of the RQCH to Up-PDU slot length $r_{\mathrm{slot}} = \tau_{\mathrm{RQCH-slot}}/\tau_{\mathrm{Up-PDU-slot}}$ depends on the implementation of the modem. Based on the 1st scenario the impact of r_{slot} on the protocol overhead O and on the mean delay of ATM cells $\overline{\tau}_d$ is investigated.

The diagram in Figure 13 shows a linear relation between r_{slot} and O. For the chosen value of $r_{\mathrm{slot}} = 0.25$ the amount of $O(r_{\mathrm{slot}} = 0.25) - O(r_{\mathrm{slot}} = 0) \approx 2.5\%$ of channel capacity is occupied by RQCH slots independent of the selected channel model. The diagram in Figure 14 considers the correlated error model and shows the influence of signalling traffic on mean cell delays. As expected, increasing r_{slot} influences delays of low priority data connections significantly stronger than delays of high priority voice and video connections.

3. Transmission of capacity requests over the RQCH

The transmission of capacity requests affects the cell delay not only by its signalling traffic but also by the delayed notification of the scheduler about new arrivals. However the delayed notification only lengthens cell delays if the scheduler is informed about an urgent cell after the ideal transmission moment of the cell is exceeded which is determined by the service strategy [5].

The simulation environment enables the measurement of this additional access delay by connecting the scheduler directly to the buffers in the terminals, in order to provide perfect knowledge about buffer occupancies. This establishes a lower bound for cell delays.

The diagrams of Figure 15 show the cell delays of uplink cells for the voice and video connections of the 1st scenario and the primary rate ISDN connection of the 2nd scenario. The diagrams compare the complementary distribution function (cdf) of cell delays with perfect knowledge about buffer occupancies (perfect uplink) with the cdf obtained when RQCH signalling is executed (real uplink). The results allow further interpretations:

Voice connections (1st scenario): The distance between the cdfs of perfect and real uplink indicates that the transmission of capacity requests adds a significant but not the main share to cell delays. The main share results from the period-oriented transmission with the uplink at the end of periods. Notice that the deterministic interarrival time of CBR cells of 6 ms is significant larger than their maximum allowed transmission delay $\tau_{d_{\max}}$ of 2 ms. Hence, the transmission of each uplink cell has to be introduced by a capacity request via the RQCH. Nevertheless, only a small share of delays is caused by the RQCH since the RQCH access protocol is optimized for short delays.

Primary rate ISDN connections (2nd scenario): The cell delays of this 2 Mbps CBR connection are caused by similar effects as observed for low rate voice connections. The impact the RQCH is the same, but successive erroneous transmissions may lead to higher delays. However, due to the higher maximum allowed transmission delay compared to voice connections, cell discarding does not occur within the visible scale.

Video connections (1st scenario): All ATM cells of a batch arrival of video connections have the same due date and are served successively. Their cell sequence is only interrupted by voice cells, MAC signalling or acknowledgments. With respect to cell delays the signalling of capacity requests after a batch arrival as well as the period-oriented transmission scheme are of minor influence. Thus, the curves for perfect and real uplink in Figure 15 nearly have the same run.

[5] With respect to the service strategy a theoretical perfect transmission sequence of buffered ATM cells can be derived from the exact knowledge about buffer occupancies. Real distributed systems can only approximate this sequence.

9. Conclusions

The paper has presented a performance evaluation of a complete protocol stack for an ATM air interface under realistic traffic and channel models. The simulation results demonstrated the necessity for a joint evaluation of MAC and ARQ protocols. Only such a joint model allows to take the following effects into account:

- Capacity reservation for transmission of acknowledgments
- Random access not only for transmission of capacity requests but also for acknowledgments
- Efficiency and stability of MAC and ARQ protocols when considering faulty protocol signalling

It has been shown that the protocol stack enables the observance of QoS for typical broadband multimedia applications. It offers a high efficiency also on very unreliable mobile radio channels with 2.5% packet errors! The fundamental approach of the protocol stack to implement a distributed ATM multiplexer at the air interface enables the flexible and easy implementation of any new ATM functionality as it is currently under discussion at the relevant standardization bodies (e.g., ABR flow control, early packet discarding, guaranteed frame rate GFR, new AAL type 2 with mini cells).

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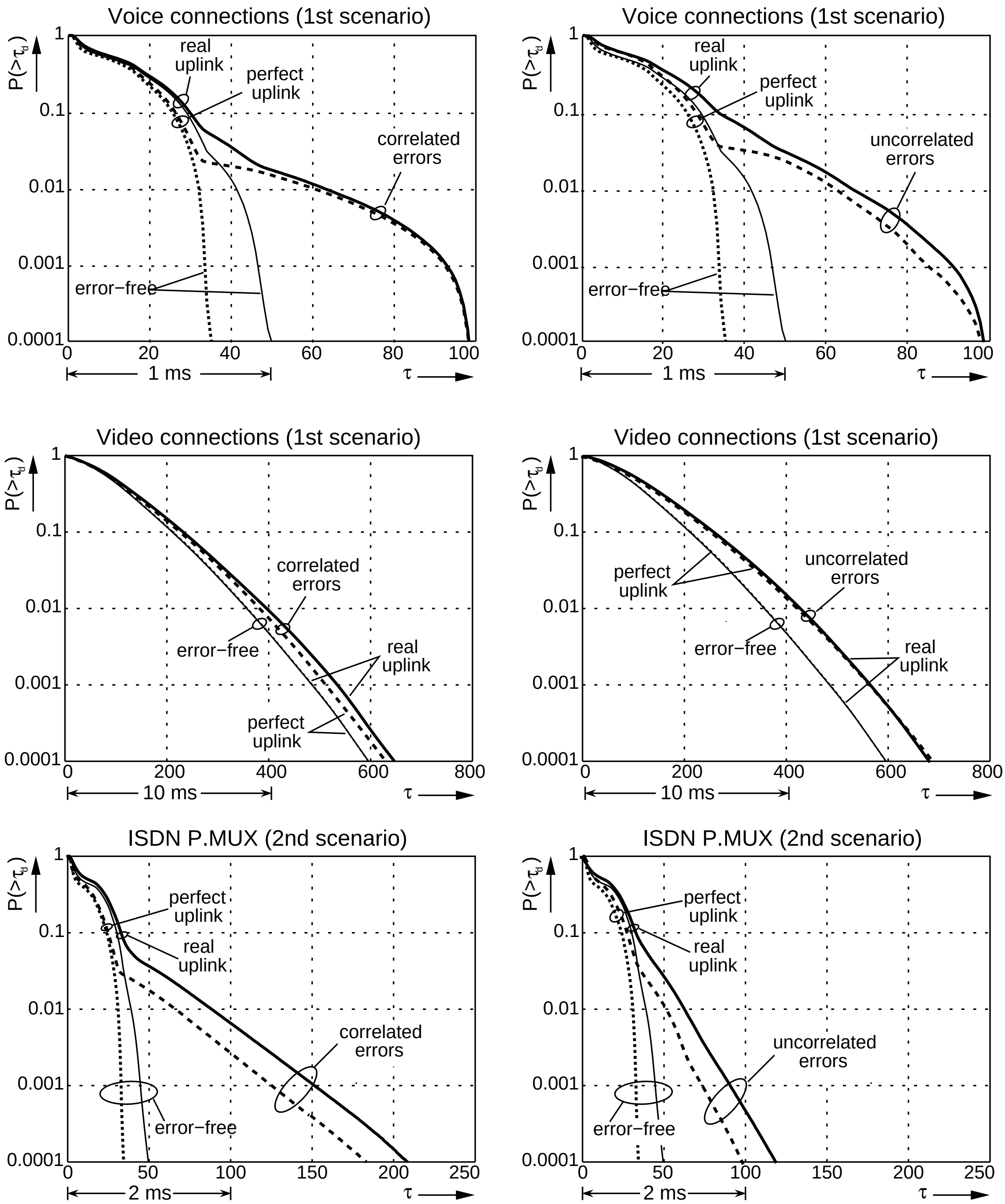

Figure 15: Cell delays (cdf) with complete knowledge of buffer occupancy (perfect uplink) in comparison to cell delays with RQCH signalling (real uplink).

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