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Wireless ATM: Performance Evaluation of a DSA++ MAC Protocol with Fast Collision Resolution by a Probing Algorithm

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Abstract — **In general, the users of wireless ATM terminals request the same functionality and quality of service as users of wired terminals. These user requirements can be transformed into the demand for building an ATM multiplexer *around* the air interface which is characterized by a radio channel inside. The main difference between this virtual ATM multiplexer around the air interface and a fixed ATM multiplexer is the distribution of the multiplexing function between wireless terminals and the base station. For the uplink this requires a frequent notification of the ATM cell scheduler in the base station about the status of the incoming buffers inside the wireless terminals. This paper focuses on different methods for transmitting capacity request messages (also designated as reservation request) over the uplink.**

I. Introduction

After the success of the *asynchronous transfer mode* (ATM) in the area of multimedia networks, demand for the transparent integration of wireless ATM terminals into fixed ATM networks has increased [1]. In general, the users of wireless (W) ATM terminals request the same functionality and *quality of service* (QoS) as users of wired terminals. These user requirements can be transformed into the demand for building a (virtual) ATM multiplexer *around* the air interface which is characterized by a radio channel inside [2]. At the ATM air interface inside this virtual ATM multiplexer, 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 (Fig. 1). Possible applications of such a W-ATM system are W-ATM LANs, cellular mobile radio, and radio in the local loop (RLL) networks.

The MAC protocol at the ATM air interface has to realize the statistical multiplexing of ATM cells in the specific scenario which is characterized by the competition of wireless terminals which are hard to coordinate. The terminals have to share the common radio channel capacity fairly and according to their negotiated QoS. The virtual ATM multiplexer of one radio cell, consisting of several wireless terminals and a central base station, can be modeled as a distributed queueing system (Fig. 2). As in fixed ATM multiplexers with low data rates (e.g., 50,000 cells/s per carrier $\approx$ 20 Mbit/s [3]), the observance of the negotiated QoS for each virtual channel (especially of real-time oriented CBR and VBR services) is only possible if an ATM cell scheduler based on static or dynamic priorities is employed. Thus, the assignment of slots to virtual channels (VC) 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. Statistical multiplexing of ATM cells on a TDMA channel is used with a slot length τ_{slot} able to carry one ATM cell together with the necessary overhead of the physical layer for synchronization, forward error correction (FEC), guard time, etc. [4].

The MAC protocol considered is called DSA++ (Dynamic Slot Assignment). The signaling frame structure (in [4] designated as signaling period) with its different burst types as well as the signaling procedures for slot reservations on uplink and downlink have been introduced in [4]. Although the DSA++ protocol was originally developed for a frequency division duplexing system, it can also be used for a time division duplexing system without major modifications (Fig. 3). This paper focuses on the transmission of capacity requests from wireless terminals to the ATM cell scheduler of the base station.

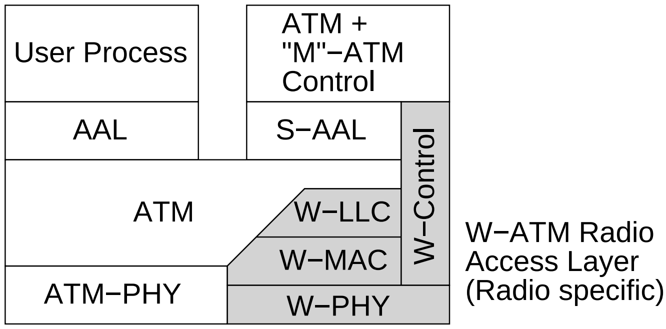

Figure 1: Protocol stack of the virtual ATM multiplexer at the ATM air interface.

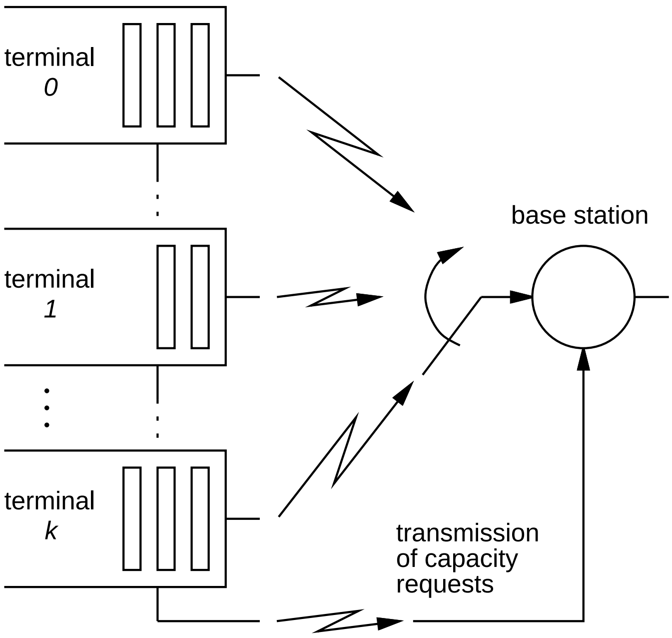

Figure 2: Modeling the MAC layer of a W-ATM network as a distributed queueing system.

II. Requirements of the ATM Cell Scheduler

The ATM cell scheduler of the virtual ATM multiplexer around the air interface executes a service strategy to determine for each slot the terminal which shall 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 [5] 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 can be combined with the execution of ABR flow control.

The main difference between the virtual ATM multiplexer and a fixed ATM multiplexer is the distribution of the multiplexing function between wireless terminals and the base station. This requires a frequent notification of the scheduler in the base station about the status of the incoming buffers inside the wireless terminals, which is performed by transmitting capacity request messages (also designated as reservation request) over the uplink. There are the following constraints:

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

Low Signaling Overhead. The signaling overhead has to be minimized, since signaling of capacity requests and transmission of ATM cells are using the same radio channel.

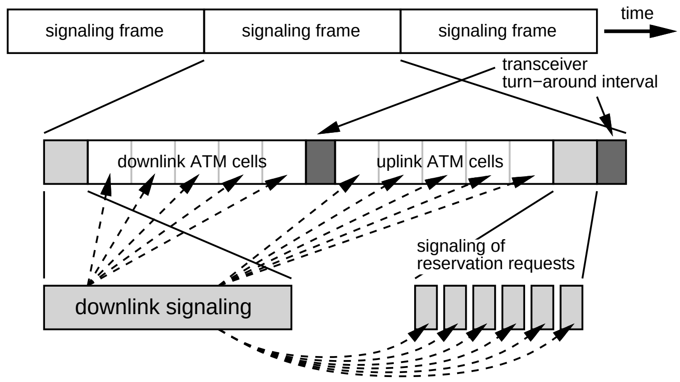

Figure 3: Signaling frame structure of DSA++ MAC protocol.

The complex problem of signaling capacity requests can be divided into following aspects:

- Coding the status of the incoming buffers
- Determining frequency and times of transmission of capacity requests
- Transmission mode of capacity requests

The procedure for coding the status of the incoming buffers in wireless terminals is adjusted to the different service strategies (one per service class) in the ATM cell scheduler. Notice that the scheduler distinguishes between virtual channels, whereas the MAC protocol distinguishes between terminals. Thus, the capacity requirements of all virtual channels of the same terminal have to be combined, at least for all virtual channels of the same service class. This further reduces the signaling overhead.

Since for each service class a specific coding algorithm is used, the term *dynamic parameters* has been introduced. It represents a generic data structure consisting of approximately two bytes. It is used in contrast to the static (connection specific) ATM traffic descriptors and QoS parameters [6] and describes the dynamic behaviour of the capacity requirements of a terminal. Each terminal has a set of dynamic parameters, one for each service class. When transmitting a capacity request message, a terminal sends the dynamic parameters of the service class with highest priority, for which the request of capacity is required.

Since VBR ATM cells are served by the relative urgency strategy, their dynamic parameters contain the due date of the most time-critical ATM cell together with the number of further cells with comparable urgency. In general, the same procedure applies to CBR. But due to the deterministic interarrival times of CBR cells, the base station does not have to be informed about the arrival of each new cell. Instead, the base station can estimate the time of the next arrival, presuming that the arrival time of the previous cell has been transmitted together with the cell

[2]. Only in the case of a faulty estimation does the wireless terminal have to transmit an explicit capacity request in order to resynchronize the estimation algorithm. The dynamic parameters of the ABR service class contain the number of waiting ABR cells in order to avoid overflow of the ABR buffers.

The most efficient transmission of dynamic parameters happens piggybacked to other packets (e.g., ATM cells or acknowledgments), whereas the unattached transmission in short bursts leads to a considerable overhead because of guard time and synchronization symbols. Thus there are the following possibilities for transmitting dynamic parameters:

- Piggybacked to ATM cells or other long messages in normal bursts
- Piggybacked to acknowledgments or other short messages in short bursts
- Unattached in short bursts

The transmission can be performed in reserved slots or in special random access slots. In order to reduce the amount of information lost in case of a collision, only the transmission of short bursts with random access is useful.

In the following it is assumed that dynamic parameters are transmitted piggybacked to ATM cells whenever possible. If a terminal wants to initiate their transmission by itself, it has to use random access in short slots. Furthermore, the base station may poll the dynamic parameters of a specific terminal by assigning a short slot.

A terminal may initiate the transmission of its dynamic parameters for two reasons:

1. If it did not request further capacity when transmitting its dynamic parameters last time, it has to signal the next arrival to the base station in order to be taken into consideration appropriately by the scheduling algorithm. This kind of terminal, which does not request further capacity, is said to be in *contention mode*. The other terminals, which did request further capacity and thus will be considered by the scheduler, are in *reservation mode*.
2. If a terminal is operating virtual channels of different service classes, the situation may occur that it did request capacity for a low-priority class (e.g., ABR) and that a cell of a higher priority class (e.g., VBR) arrives afterward. Although the terminal is in reservation mode, the scheduler will consider it with too low priority. Thus, the transmission of the new VBR dynamic parameters piggybacked to an ABR cell may happen too late. Therefore it is useful that the terminal transmits its VBR dynamic parameters in random access.

If the transmission of dynamic parameters fails, a terminal is assumed to be in reservation mode although the base station is considering it to be in contention mode. To guarantee stability of the protocol, the terminal has to be able to detect such situations. This can easily be realized if the latest scheduled priority of a signaling frame is signaled by the downlink signaling burst. By comparing the scheduled priority with its own requirements, a terminal may detect that it has not been considered by the scheduler and will retransmit its dynamic parameters immediately.

III. Contention-free Transmission of Capacity Requests

In contention-free W-ATM MAC protocols the dynamic parameters are always transmitted by polling (or piggybacked to ATM cells). This reduces the complexity of the MAC layer, since complex collision resolution algorithms are not to be implemented. Wireless terminals are only allowed to transmit their dynamic parameters after an explicit or implicit invitation by the base station, but they can no longer initiate the transmission by themselves. Therefore, each station has to be polled at least after a specific interval, the length of which depends on the virtual channel with the shortest maximum delay operated by this terminal.

It has to be noted that even in contention-free MAC protocols a specific narrowband channel with random access for registration of new terminals is necessary. It can be realized in combination with a beacon and paging channel by superimposing the signaling frame structure with a super frame structure.

In this paper we consider a polling algorithm with implicit reservation of poll slots. This has the advantage of a low signaling effort at the downlink for slot reservation messages resulting in a reduced signaling overhead. In every frame, each terminal will have at least one possibility for transmitting its dynamic parameters. This is normally performed piggybacked to ATM cells. If a terminal is not allowed to transmit an ATM cell in a frame, a short poll slot will be assigned to it at the end of the frame. If the terminals are numbered by continuous, increasing identifiers

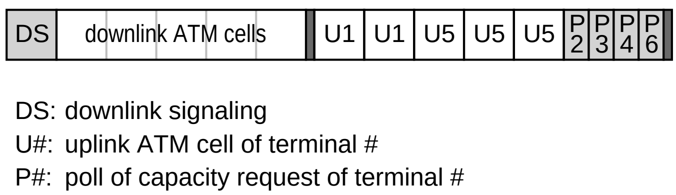

Figure 4: Example of implicit reservation of poll slots at the end of a signaling frame.

from a finite identifier space,[1] an explicit signaling of poll slot reservations is not necessary. Figure 4 gives an example of slot reservations in a signaling frame that is opened by a downlink signaling burst containing one announcement message for each downlink ATM cell slot and one reservation message for each uplink ATM cell slot. This burst is followed by the downlink ATM cell bursts. Ahead of the uplink ATM cell bursts, a transceiver turnaround interval is inserted. The frame is finished by the poll slots and another transceiver turnaround interval.

In Section V the performance of this MAC protocol will be evaluated and compared with a contention-based MAC protocol.

IV. Contention-based Transmission of Capacity Requests

The usage of random access gives terminals the possibility to initiate the transmission of their dynamic parameters by themselves. This has a considerable advantage for bursty and real-time-oriented VC, especially with VBR and narrowband CBR services. When employing random access, a stable and fast algorithm for collision resolution is necessary. Polling is used to support random access by polling the terminals whose probability of success is higher than the throughput of random access [7].

The frame structure of the DSA++ protocol gives rise to following constraints for random access [7]:

- The result in a random access slot is broadcasted to the wireless terminals as feedback message inside the next downlink signaling burst. Thus, there is the situation with delayed feedback as described in [8].
- Each frame can provide nearly any number of random access slots. The maximum number is only limited by the size of a downlink signaling burst, because it has to carry the necessary signaling 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, because 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 frames may be used to enable fast transmission of feedbacks [4]. In our protocol a maximum frame length is defined by the number of reservation messages in a downlink signaling burst. This burst has the same length as a downlink ATM cell burst (approx. 53 bytes), but due to its importance for protocol stability its contents are protected by a special FEC. Thus, we assume 20 reservation messages per downlink signaling burst. Each reservation of a random access slot as well as each feedback message replaces a reservation message for an ATM cell slot. Thus, frames are automatically shortened with increasing number of random access slots.

Delays in random access are also influenced by the used collision resolution algorithm. We consider an unblocking adaptive identifier splitting algorithm [8] that takes advantage of the known number of stations in contention mode, since only registered terminals are allowed to request capacity. This algorithm has been analyzed in [9], where it is called the *probing algorithm.*

At the beginning of each frame the probing algorithm divides the identifier space (of size N) into a variable number t of consecutive intervals and assigns one random access slot to each interval. The lth interval starts with terminal i_l and ending 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 downlink signaling burst signals the interval division to the terminals by transmitting the start identifier i_l of each interval. Furthermore, it is possible to poll specific terminals in dedicated short slots. Such terminals are not allowed to send in random access slots.

The width of each interval is determined by considering the probability $p_{\text{send},i}$ that terminal i will send in a random access slot. For terminals in reservation mode $p_{\text{send},i}$ is zero. For terminals in contention mode the base station approximates $p_{\text{send,i}}$ by modeling the arrival process of the next ATM cells by a simple Poisson process with parameter λ_i. With this model $p_{\text{send},i}$ corresponds to the probability of at least one arrival at terminal i during the interval $t_{\text{slot}} - t_{\text{last send},i}$ since the last transmission of its dynamic parameters (in short slots or piggybacked to ATM cells), with t_{slot} being the time of the considered random access slot at the end of the signaling frame,

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

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

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

With the parameter W the probability of a successful transmission can be adjusted. The analysis in [9] 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 frame 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),

[1] E.g., assigned by the base station during a registration procedure.

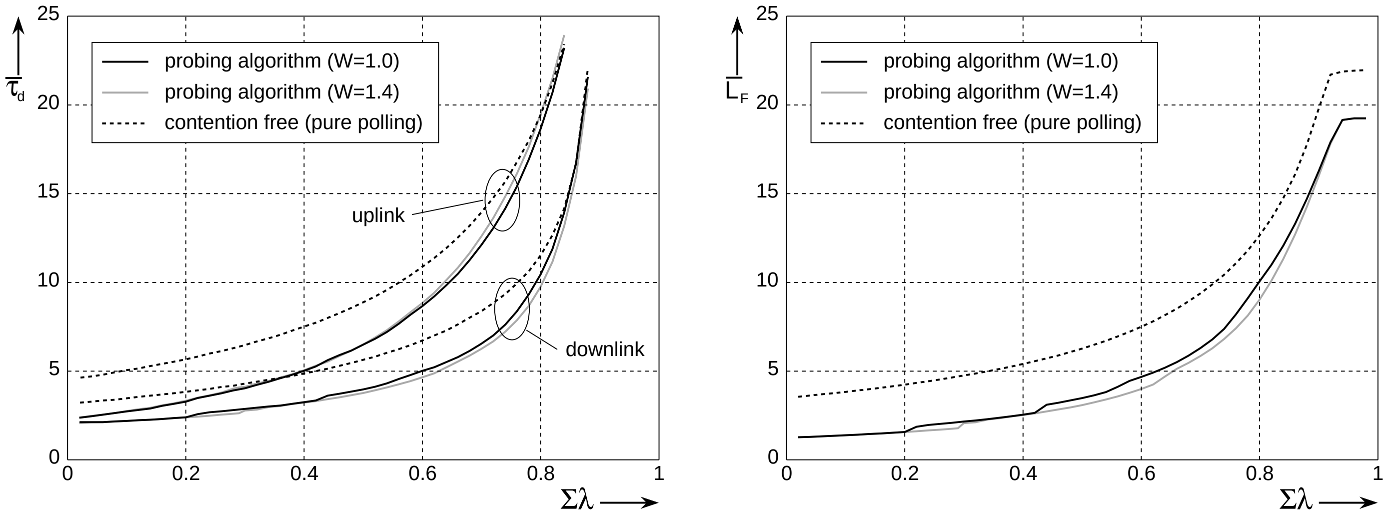

Figure 5: Results of scenario with symmetric Poisson load: average delay of ATM cells $\overline{\tau}_d$ and average frame length $\overline{L}_F$ over overall load $\sum\lambda$; here τ_d, L_F and $\sum\lambda$ are normalized to τ_{slot}.

$t_{\text{last send},i}$ is set to t_{slot} and C_i is set to 1 for all involved stations. 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.

The above approximation requires a special treatment of terminals that are involved in a collision for several signaling periods. To avoid high delays, terminals that have not been involved in a collision before are not allowed to enter an interval containing terminals that are collided more than once. Furthermore, a collided terminal is not allowed to enter an interval, whose size K_l is greater than or equal to the size of the interval of the previous frame to which the considered collided terminal belonged. This forces a decrease in interval sizes during an ongoing collision resolution cycle.

The correct determination of the parameter λ_i is a difficult task, since it cannot be derived from the ATM traffic descriptors [6]. An adaptive algorithm based on traffic measurements seems to be an adequate solution.

V. Simulation Results

The performance of the two considered protocols for the transmission of capacity request messages has been evaluated by stochastic simulations. We considered a TDD air interface (maximum 20 reservation messages per downlink signaling burst) with an overall data rate according to 50,000 ATM cells per second (uplink and downlink together) resulting in a slot length for transmitting an ATM cell $\tau_{\text{slot}} = 20\mu$s. Since the length of a short slot $\tau_{\text{short slot}}$ has a considerable influence on system performance, we parametrized it by $r_{\text{short slot}} = \tau_{\text{short slot}}/\tau_{\text{slot}}$. If not stated otherwise, $r_{\text{short slot}} = 4$ is assumed. This seems to be a realistic value, taking into account the overhead for the training sequence if an equalizer is employed, or for synchronization symbols if multicarrier modulation is used.

The length of a simulation run has been controlled by prescribing a relative error supported by the LRE algorithm [10], which considers correlations between measured values. The relative error of all results is lower than 5%.

Three simulation scenarios have been considered.

A. Scenario with Symmetric Poisson Load

The first scenario assumes 10 terminals with one virtual channel (VC) each. The load results from Poisson sources and is equally distributed between the VCs on uplink and downlink. The diagrams in Fig. 5 contain the average delay of ATM cells $\overline{\tau}_d$ as well as the average frame length $\overline{L}_F$ over the overall load $\sum\lambda$. Here τ_d, L_F and $\sum\lambda$ are normalized to τ_{slot}. The signaling effort S_{DynP} and efficiency ρ_{DynP} (probability of success) of the transmission of capacity requests in short slots are given by Fig. 6. In

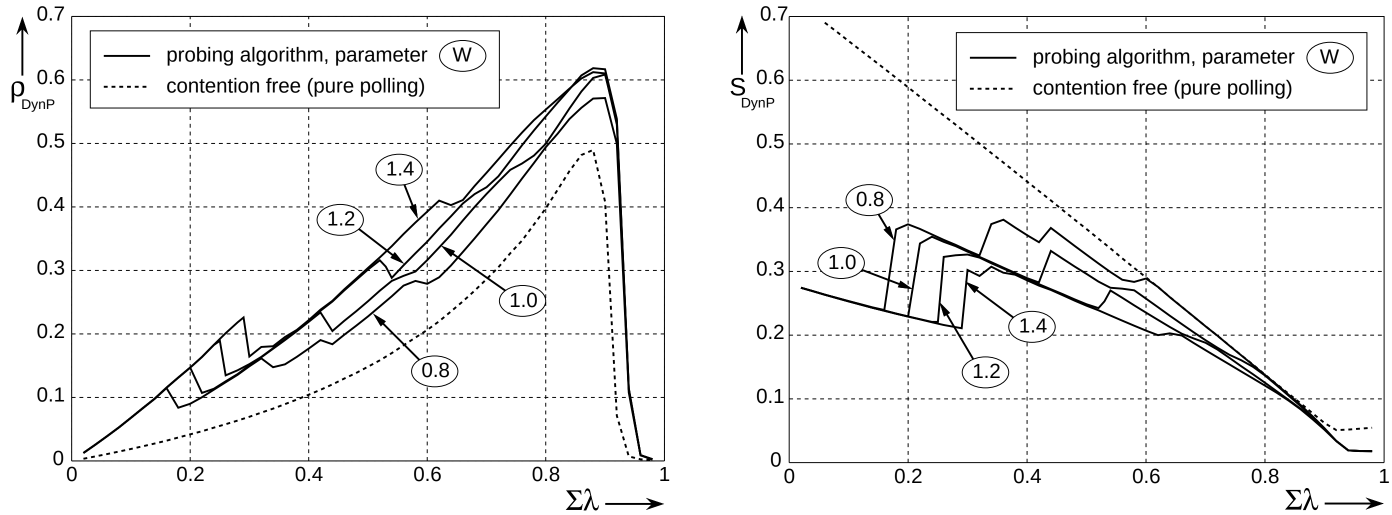

Figure 6: Results of scenario with symmetric Poisson load: signaling effort S_{DynP} and efficiency ρ_{DynP} (probability of success) of the transmission of capacity requests in short slots over overall load $\sum \lambda$.

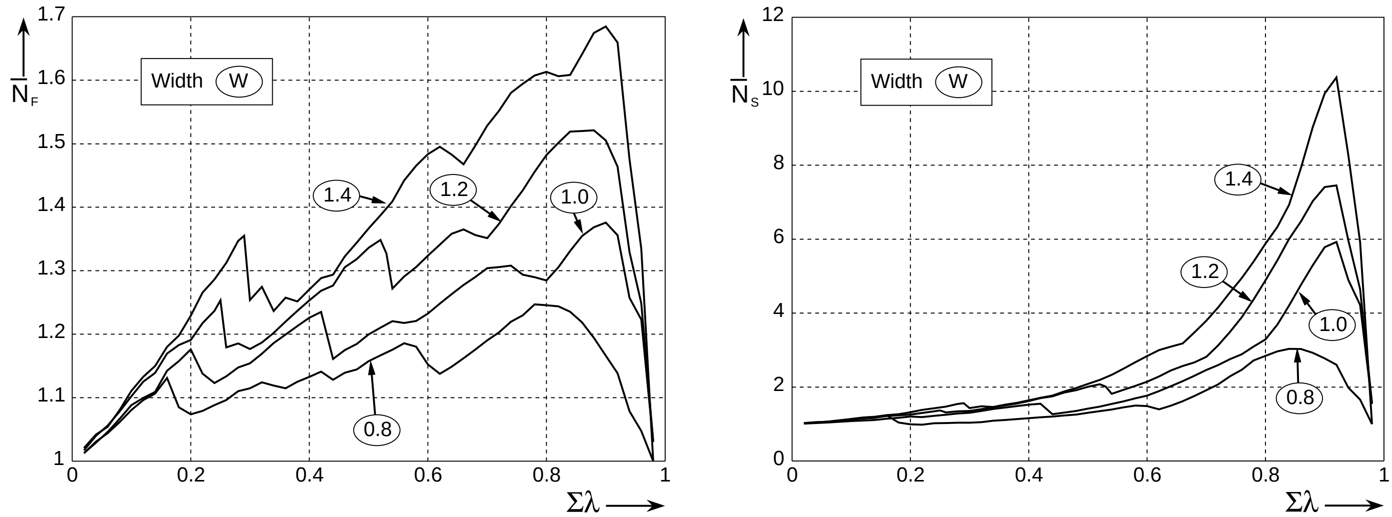

Figure 7: Results of scenario with symmetric Poisson load: mean number of signaling frames $\overline{N}_F$ till successful transmission in random access and average delay in random access $\tau_{d,\,\mathrm{RACH}} = \overline{N}_S \cdot \tau_{\mathrm{slot}}$ over overall load $\sum \lambda$.

Fig. 7 the mean number of signaling frames $\overline{N}_F$ till a successful transmission in random access and as the average delay $\tau_{d,\,\mathrm{RACH}} = \overline{N}_S \cdot \tau_{\mathrm{slot}}$ in random access is shown. $\tau_{d,\,\mathrm{RACH}}$ is measured from the first access to a short random access slot till the reception of a positive feedback. The width parameter W of the probing algorithm has been varied from 0.8 to 1.4.

It can be seen that lower values of W lead to shorter delays in random access, but reduce the efficiency ρ_{DynP}. The faster random access reduces the average delay of uplink ATM cells, and the lower efficiency ρ_{DynP} together with the higher signaling effort S_{DynP} increases the average delay of downlink ATM cells. The value $W = 1.0$ seems to be a good compromise between delays and efficiency. The contention-free protocol produces a considerably higher signaling overhead S_{DynP} than the probing algorithm. This results in a longer average frame length $\overline{L}_F$ and thus produces higher delays of ATM cells on uplink and downlink.

The simulations have shown that most signaling frames are shortened because of not enough ATM cells to be delivered. Thus, an increase of the number of reservation messages per downlink signaling burst by reducing its error protection is not useful.

B. Scenario with Asymmetric Poisson Load

In the second simulation scenario, the Poisson load of the first scenario is asymmetrically divided between the VCs. VC(i) has a load of $\lambda_i = \sum \lambda / 2^{i+1}$ on uplink and downlink each. Figure 8 shows the average delay of ATM cells $\overline{\tau}_d$ over the overall load $\sum \lambda$ as well as the complementary distribution function (CDF) of delays per VC for

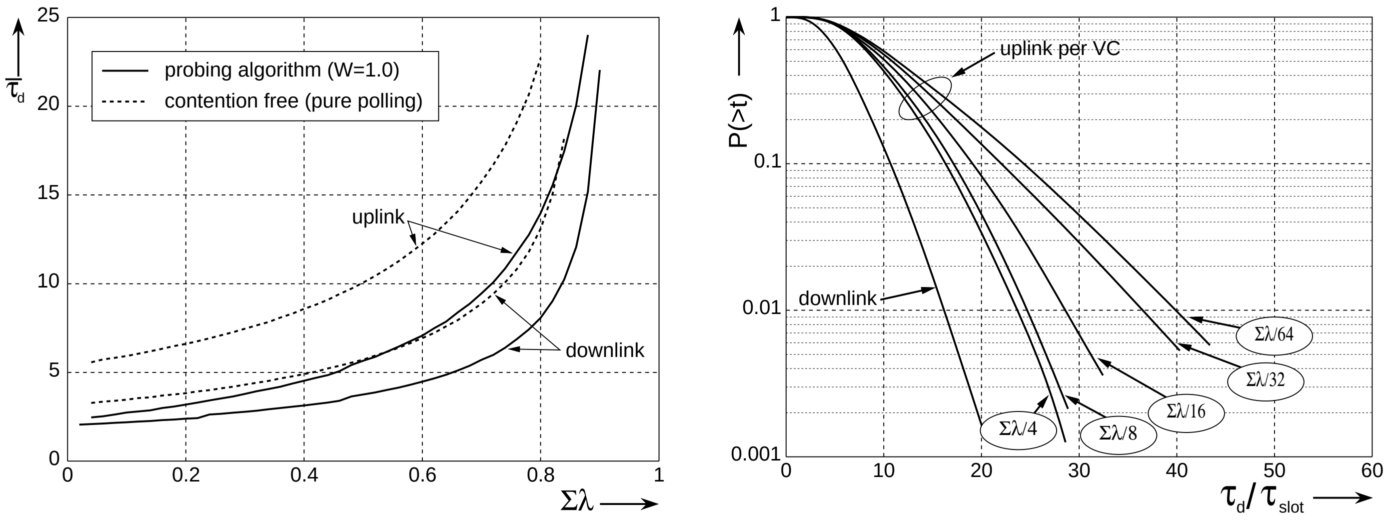

Figure 8: Results of scenario with asymmetric Poisson load: average delay of ATM cells $\overline{\tau}_d$ over overall load $\sum \lambda$ and complementary distribution function of delays per virtual channel with probing algorithm at $\sum \lambda = 0.75$.

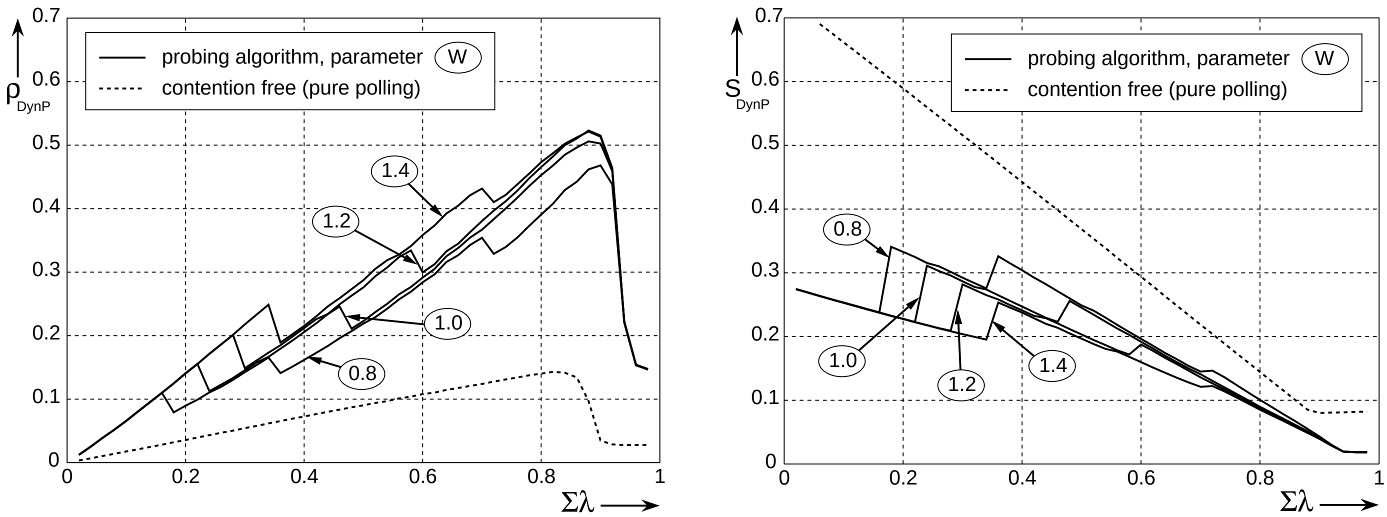

Figure 9: Results of scenario with asymmetric Poisson load: mean number of signaling frames $\overline{N}_F$ till successful transmission in random access and average delay in random access $\tau_{d,\,\mathrm{RACH}} = \overline{N}_S \cdot \tau_{\mathrm{slot}}$ over overall load $\sum \lambda$.

a load $\sum \lambda = 0.76$ with the probing algorithm. It can be seen in the CDF that with the probing algorithm all downlink cells suffer the same delay, but that the delays of the uplink cells grow with decreasing λ_i, since the probability of first requesting capacity before transmitting an ATM cell increases. By comparing the mean delays with the delays of the symmetric scenario one sees that asymmetric load leads to a considerable performance loss of the contention-free protocol. Figure 9 shows that the efficiency of polling has decreased rapidly compared to symmetric load, leading to a higher signaling effort S_{DynP} of the contention-free protocol.

C. Multimedia Scenario

The last simulation scenario considers more realistic source models of a multimedia application. The simulation model is according to [7]. The parameters of the simulation scenario are summarized in Table 1.

Table 1: Parameters of Multimedia Scenario

Service	ATM class	λ p. VC	#WT	Load	$\tau_{d\max}$	$\tau_{d\max}/\tau_{\mathrm{slot}}$
Voice	CBR	64 kbps	4	3%	2 ms	100
Video	VBR	1 Mbps	2	22%	20 ms	1000
Data	ABR	460 kbps	10	50%	Undef.	Undef.

The scenario has been used to evaluate the influence of the length $\tau_{\mathrm{slot}}/r_{\mathrm{short\,slot}}$ of short slots on delays. In Figure 10 the mean delay of ATM cells from different service classes is shown for the probing algorithm when varying $r_{\mathrm{short\,slot}}$. It can be seen that increasing $r_{\mathrm{short\,slot}}$ leads to shorter delays, but only a slightly further improvement can be expected with $r_{\mathrm{short\,slot}} > 6$.

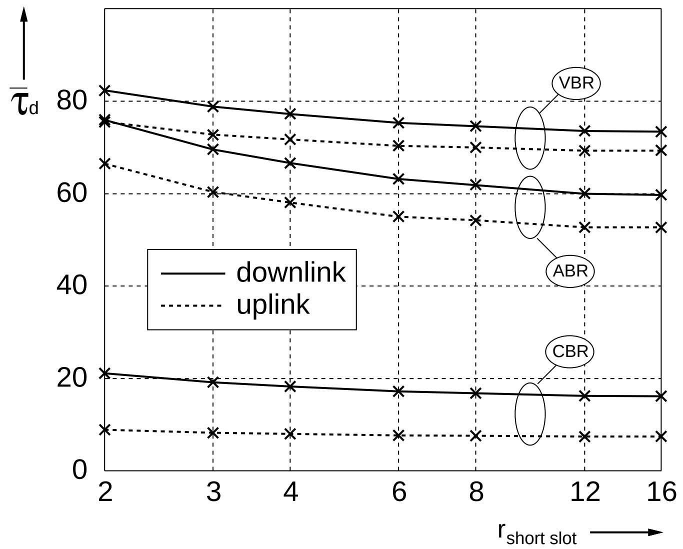

Figure 10: Results of multimedia scenario: mean delays τ_d of ATM cells for probing algorithm with different lengths of short slots $\tau_{\text{short slot}} = \tau_{\text{slot}}/r_{\text{short slot}}$.

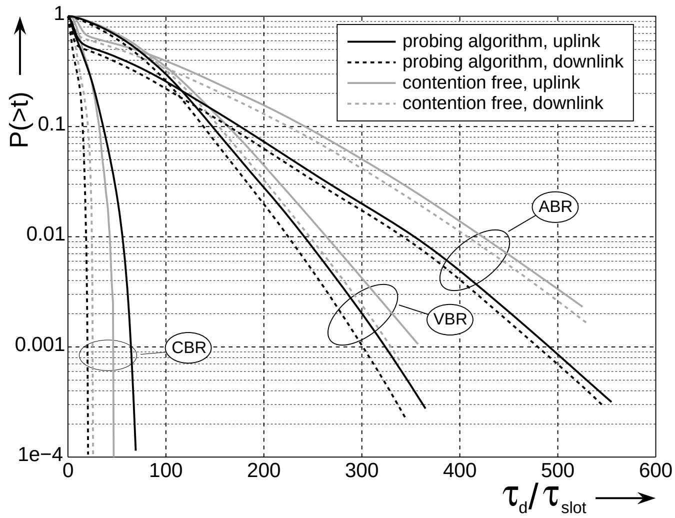

Figure 11: Results of multimedia scenario: complementary distribution function of ATM cell delays.

The comparison of the MAC protocols has been performed with $r_{\text{short slot}} = 4$. The complementary distribution functions of delays of ATM cells from all service classes are compared in Fig. 11. Delays are always higher with the contention-free protocol because of the larger signaling overhead for transmitting capacity requests. Only the delays of uplink CBR cells are shorter with the contention-free protocol since for each cell first a capacity request has to be transmitted, which may be involved in a collision, when using the probing algorithm. But due to guaranteed maximum delays during collision resolutions with the probing algorithm, no CBR uplink cells are too late.

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