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Service Strategy for VBR Services at an ATM Air Interface

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Abstract **— Providing and guaranteeing *Quality of Service* requested by a user is an important and challenging task in telecommunication networks. Within ATM networks the negotiated service requirements have to be fulfilled using several methods of *traffic management*. Wireless ATM introduces a new dimension of complexity into these methods. While ATM applications in wireless ATM terminals request the same functionality and Quality of Service as in wired ATM terminals, the network characteristics like maximum transmission rate and error ratio differ. The methods for handling the user demands have to be adapted to this new environment. A radio cell of a cellular wireless or mobile ATM network corresponds to a virtual ATM multiplexer with an internal radio channel. For an analytic approach this multiplexer is modelled as a distributed queueing system. A central scheduler located in the base station determines the order of cell transmission and a MAC protocol organizes the realization of the transmission order on the radio channel. This paper focuses on the scheduling policy required to guarantee the requested Quality of Service especially for real-time VBR services. A scheduling strategy with dynamic priorities is developed and analysed using stochastic simulations.**

I. Introduction

The *asynchronous transfer mode* (ATM) has become widely accepted in the area of high-speed and multimedia networks. During the last few years a demand for providing transparent integration solutions of wireless ATM terminals into those networks has arisen. Possible applications include cellular mobile radio, wireless ATM-LANs and Radio in the Local Loop [1]. Although the functionality and the *Quality of Service* requested by users in a wireless environment is similar to the one needed in a standard (wired) ATM network the more difficult and restrictive conditions of the air interface require different methods in order to satisfy the user needs.

The air interface can be modelled as a virtual ATM multiplexer with an internal radio channel [2]. Inside this multiplexer the physical layer and parts of the ATM layer have to be replaced by a wireless physical layer, a *medium access control* (MAC) layer and a *logical link control* (LLC) layer (cf. Fig. 1).

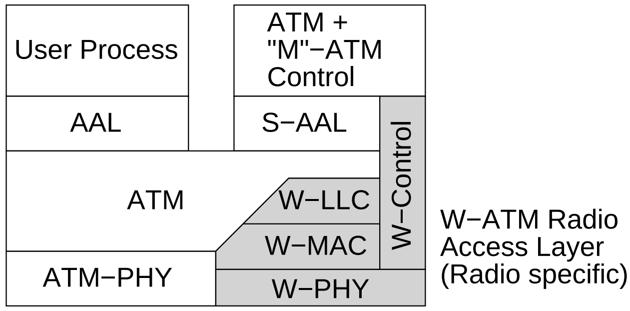

Fig. 1: Protocol stack of the virtual ATM multiplexer at the ATM air interface

Quality of service in ATM networks can be described with a set of parameters observable at UNI interface between a terminal and the access node [3, 4]. The QoS is negotiated between the user and the service provider during the connection establishment phase and fixed with a traffic contract. It has to be guaranteed by the network for the lifetime of a connection. Since ATM traffic is experienced with statistical characteristics and a cell oriented transmission, no static long-term capacity reservation is used in ATM networks. Instead short-term dynamic allocation methods are introduced. In order to reflect the various capacity requirements of different virtual connections, ATM service classes have been defined [3].

The main goal of traffic management [3] in ATM networks is to observe, control and enforce Quality of Service. Appropriate methods have to be implemented in terminals as well as in network nodes. Well known aspects of traffic management policies are the *connection admission control* (CAC) and the *congestion control* (CC) [5]. This paper focuses on a different approach of QoS control for wireless ATM networks. The limited resource of transmission links between ATM network nodes is shared between several virtual connections (VC). Network nodes (switches and multiplexers) have to determine the transmission order of cells to be sent over the links. Thus, an *ATM cell scheduler* is introduced for each output link that controls the statistical mul-

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tiplexing of cells by employing an appropriate service strategy. Its goal is to optimize the resource allocation based on short-term demands of VCs and their negotiated Quality of Service. Appropriate service strategies usually focus on two key targets: avoiding overflow of buffers and controlling delays of ATM cells. Which issue the strategy has to focus on strongly depends on the transfer rate of the link. While a fast transfer rate of 155 Mbit/s and more in wired ATM networks causes buffer overflows to be the more critical aspect, with slow transfer rates cell delay guarantees become more difficult to fulfil. Therefore, in high-speed networks, traffic management is usually executed by CAC and CC policies. For wireless ATM applications with a radio link transfer rate of about 20 Mbit/s, [6], the service strategy plays a major role in providing Quality of Service.

In this paper we analyse and compare different service strategies with static and dynamic priorities. A parametrization algorithm considering capacity requests and Quality of Service constraints is developed for the dynamic priority discipline *Relative Urgency*.

II. Requirements of the ATM cell scheduler

The ATM cell scheduler in a wireless environment is characterized by the distribution of the sending buffers on terminals (uplink ATM cells) and the base station (downlink ATM cells). The scheduler in the base station has only a limited information about the buffer state of terminals. It is a task of the MAC protocol to offer a fast and reliable channel for transmitting so called *capacity request messages* coding the buffer state of terminals [7, 2].

The main goal of a service strategy employed by the scheduler is to control cell delays. In general, this includes the mean cell delay, the cell delay variation and the maximum cell delay. Since ATM cells which exceed their maximum delay will usually be discarded by the receiving application, we focus the schedulers activity on controlling the maximum cell delay. Thus, we consider cells having exceeded their maximum delay being lost, regardless if they were transmitted or discarded by the QoS control. The requirements of the VCs concerning the maximum cell delay strongly depend on the service class of the connection. For the UBR service class no QoS is defined, while ABR class connections have QoS constraints but no short-term demands regarding the maximum cell delay. CBR like VBR services have very tight limits for the maximum cell delay [8]. A service policy for the scheduler has to be defined in order to differentiate between these service classes as well as to handle connections of the same class.

Considering their special characteristics, static priorities are introduced between the service classes (CBR $>$ VBR $>$ ABR $>$ UBR). CBR connections can be easily handled due to their deterministic traffic characteristic. For ABR services the algorithms applied for fixed ATM multiplexers are used [9], while the UBR service class does not need specific handling. Simple strategies like First-Come-First-Serve (FCFS) are sufficient to guarantee a fair resource sharing. Only VBR services need more attention as the mean cell delay as well as the probability of exceeding the maximum cell delay have to be minimized. Appropriate service disciplines for VBR connections have to be judged considering the calculation overhead and the probability that the negotiated QoS guarantees can be fulfilled.

III. Service disciplines for real-time VBR connections

For analyses of possible service disciplines for VBR connections we assume a complete information of the scheduler about all buffer states. Furthermore we assume error-free transmission and unlimited buffers. Thus the VBR service class is modelled as a G/D/1 queueing system, cf. Fig. 2. The G/D/1 model allows an analytic approach for the comparison of different service strategies. In more realistic systems these services disciplines have a similar behaviour, as simulations in section IV will show.

The scheduler has to minimize the probability of exceeding the maximum delay $\tau_{d max}$ for each real-time VBR VC[1]. $\tau_{d max}$ can be added to the arrival time of an ATM cell to determine its latest transmission time (deadline, due-date) required to avoid a cell loss. Therefore, a service discipline considering the deadlines of cells seems to be the appropriate approach. In order to verify this theory, we compare static and dynamic priorities based service policies in M/D/1 queueing systems using analytic methods and stochastic simulations. Additionally, the impacts of using non-Markovian traffic sources are determined by stochastic simulations.

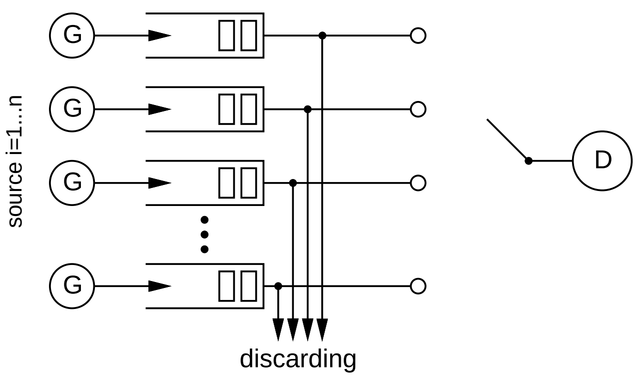


Fig. 2: Modelling the VBR service class as a distributed G/D/1 queueing system

The priority for a specific VC is assigned during call establishment depending on the set of QoS requirements com-

[1] We assume $\tau_{d max}$ as a fraction (e.g. 20%) of the maximum end-to-end cell transfer delay.

mitted to the existing VC and the requests of the new connection. Thus, the priorities of all connections have to be re-calculated eventually if the new VC is accepted by the CAC. This requires the CAC to apply admission criteria similar to the ones used for the service strategy of the scheduler. For the following analysis we assume that no VCs are violating their data rate requirements, which are fixed in the service contract. This has to be guaranteed by a traffic parameter control [5].

In order to assign appropriate priorities (static or dynamic) the distribution function (DF) of the cell delay has to be known. In this paper we choose a simple approximation of this function using a negative exponential distribution. The quality of this approximation is sufficient because the M/G/1 queueing system has a similar behaviour as a negative exponential distribution for high quantiles of the DF [10]. Regarding the complementary DF of cell delays for a certain VC the *cell loss ratio* (CLR) of this VC corresponds to the function value taken at the maximum cell delay τ_{dmax}.

A. Analysis of a static priority discipline

With the static priority discipline each VC is assigned a priority class during connection establishment. The scheduler executes a non-preemptive (NONPRE) static priority discipline between the VCs i.e. a cell of a priority class i can only be transferred if no ATM cell with higher priority is waiting for transmission. Within one priority class FCFS is used.

The assignment of static priorities to VCs is a discrete optimization problem. The weighed probability of exceeding τ_{dmax} which correspond to the total number of cell losses have to be minimized without violating the individual CLRs of the virtual connections. VCs with different CLRs may be assigned the same priority class depending on the scenario of connections. For this optimization the distribution function of the cell delays for a priority class i is needed. In M/D/1/FCFS/NONPRE queueing systems the first two moments W_i and $W_i^{(2)}$ of the DF for class i with a deterministic normalized service time $\beta^{(n)} = 1$, the mean arrival rate λ_i and a total number of N priority classes can be expressed by [11, 12]:

$$\lambda_{<k} = \sum_{j=0}^{k-1} \lambda_j \qquad \lambda_{\leq k} = \sum_{j=0}^{k} \lambda_j \tag{1}$$

$$W_i = \frac{\lambda_{\leq N}}{2(1-\lambda_{\leq i})(1-\lambda_{<i})} \tag{2}$$

$$W_i^{(2)} = \frac{\lambda_{\leq N}\lambda_{<i}}{2(1-\lambda_{\leq N})(1-\lambda_{<i})} + \frac{\lambda_{\leq N}}{3(1-\lambda_{\leq i})(1-\lambda_{<i})^2} + \frac{\lambda_{\leq N}\lambda_{\leq i}}{2(1-\lambda_{<i})^2(1-\lambda_{\leq i})^2} \tag{3}$$

Applying the approximation by a negative exponential distribution the parameter μ and p of the approximated complementary DF [10]

$$P(\leq t) = 1-(1-p)e^{-\mu t} \tag{4}$$

can be calculated with W_i and $W_i^{(2)}$ of the original distribution:

$$p = 1 - \frac{2W^2}{W^{(2)}} \qquad \mu = \frac{2W}{W^{(2)}} \tag{5}$$

The formal optimization problem intends to minimize the total number of lost cells considering the individual constraints of all VCs:

Minimize

$$\begin{aligned} \overline{CLR} &= \frac{1}{\lambda_{\leq N}} \sum_{i=1}^{N} \lambda_i P_i(> \tau_{dmax,i}) \\ &= \frac{1}{\lambda_{\leq N}} \sum_{i=1}^{N} \lambda_i (1-p_i) e^{-\mu_i \tau_{dmax,i}} \end{aligned} \tag{6}$$

subject to the constraints:

$$P_i(> \tau_{dmax,i}) \leq CLR_i \qquad \forall \quad 1 \leq i \leq N \tag{7}$$

The solution of this optimization problem can be found using combinatorial methods. As this process has to be executed under real-time conditions, an exhaustive search for the optimal priority assignment becomes impossible if the number of VCs increases. The number of permutations range between $N!$ and N^N. Intelligent strategies can be used with reduced calculation effort for finding any combination fulfilling the constraints.

B. Analysis of dynamic (deadline oriented) priority disciplines

Deadline oriented priorities can be used if each priority class has a maximum delay corresponding to the maximum queueing time of a single job (here: ATM cell) after that a service (here: transmission) has to be started. Therefore, each individual cell has a deadline or due-date $\tau_{DD_i} = t_0 + \tau_{dmax,i}$ (t_0 is the arriving time of the cell at the queueing system) for the beginning of the transmission. The priority of a cell of VC i increases while approaching this deadline:

$$q_i(t) = \tau_{DD_i} - t = \tau_{dmax,i} - (t - t_0) \tag{8}$$

The scheduler selects the cell with lowest $q_i(t)$ (highest urgency) for the next transmission. Several authors have shown the ability of this strategy to minimize the total number of cell losses [13, 14]. A generalization of this *Earliest Due Date First* (EDD) discipline is obtained if the deadline of a cell is determined according to the τ_{dmax} *and* the CLR of the corresponding virtual connection. τ_{DDi} can be interpreted as a *relative urgency* of a cell.

1) The relative urgency scheduling discipline If τ_{DDi} is taken as the urgency of a specific cell from VC i, it has to consider the deadline of a cell and the CLR of that connection. $\tau_{dmax,i}$ is replaced by U_{0i}, the *urgency start offset*:

$$U_{RUi}(t) = U_{0i} - (t - t_0) \tag{9}$$

The cell with minimal $U_{RUi}(t)$ is selected for the next transmission by the scheduler.

After introducing the mean urgency $\overline{U}_0$, the (complementary) DF of cell delays for f-quantiles $f \to 1$ (N priority classes, deterministic service time $\beta^{(n)} = 1$) can be expressed by:

$$\overline{U}_0 = \frac{\sum_{i=1}^{N} \lambda_i U_{0i}}{\lambda_{\leq N}} \tag{10}$$

$$P(W_i > t) = (1-p)e^{-\mu(\overline{U}_0 - U_{0i})}e^{-\mu t} \tag{11}$$

p and μ correspond to the parameters of the negative exponential distribution used for the approximation of the DF (4) parameterized with the DF for the M/D/1/FCFS queueing system ($\lambda_{FCFS} = \lambda_{\leq N}$). Important attributes of the M/D/1/FCFS/RU model are:

- One priority class for all VCs (FCFS) can be achieved with the same U_{0i} for all VCs.
- Static priorities between VC i and VC j can be approximated with $U_{0i} \ll U_{0j}$ or $U_{0i} \gg U_{0j}$.
- If the urgency start offset is equal to the maximum delay $U_{0i} = \tau_{dmax,i}$ the EDD strategy is obtained.
- According to [15] the times T_i and T_k with the f-quantile of the delay DF differ for $f \to 1$ by the difference of their urgencies.

Using this knowledge a parametrization algorithm for the urgency start offset U_0 can be developed.

2) Parametrization algorithm for the relative urgency scheduling discipline The parametrization algorithm for the urgency start offsets has to ensure that all virtual connections share the transmission channel according to their CLR and maximum delay requirements. Therefore, an optimization approach similar to the one presented in section III.A has to be used. With the complementary DF $P_i(> \tau_{dmax,i})$ used to determine the CLR the optimization problem can be defined:

Minimize

$$\begin{aligned}\overline{CLR} &= \frac{1}{\lambda_{\leq N}} \sum_{i=1}^{N} \lambda_i P_i(> \tau_{dmax,i}) \\ &= \frac{1}{\lambda_{\leq N}} \sum_{i=1}^{N} \lambda_i (1-p) e^{-\mu(\overline{U}_0 - U_{0i})} e^{-\mu \tau_{dmax,i}}\end{aligned} \tag{12}$$

subject to the constraints

$$P_i(> \tau_{dmax,i}) = (1-p)e^{-\mu(\overline{U}_0 - U_{0i})}e^{-\mu\tau_{dmax,i}} \leq CLR_i \tag{13}$$

Thus, the total number of cell losses is minimized without violating the connection specific CLR demands. The considered optimization problem is nonlinear and multivariable. Therefore, any strategies trying to solve this system within the experienced real-time conditions would encounter severe difficulties. A simple approach searching for one suboptimal solution focuses on determining one set of start urgency offsets meeting the constraints.

From (13) equation (14) can be determined:

$$\overline{U}_0 - U_{0i} \geq C_i \qquad \forall \quad 1 \leq i \leq N \tag{14}$$

with:

$$C_i = -\frac{1}{\mu} \ln\left(\frac{CLR_i}{1-p}\right) - \tau_{dmax,i} \tag{15}$$

Condition (13) can be changed to an equation:

$$\overline{U}_0 - U_{0i} = C_i \qquad \forall \quad 1 \leq i \leq N \tag{16}$$

Now one U_{0i} can be fixed and the other urgency offsets be calculated using (16).

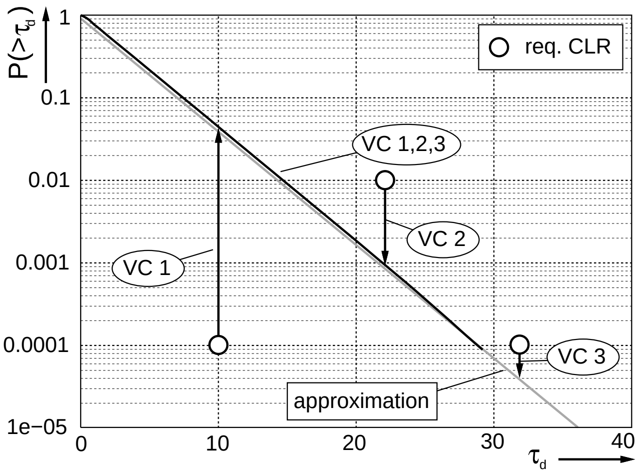
The developed parametrization algorithm is called *Optimized Relative Urgency* (ORU) strategy.

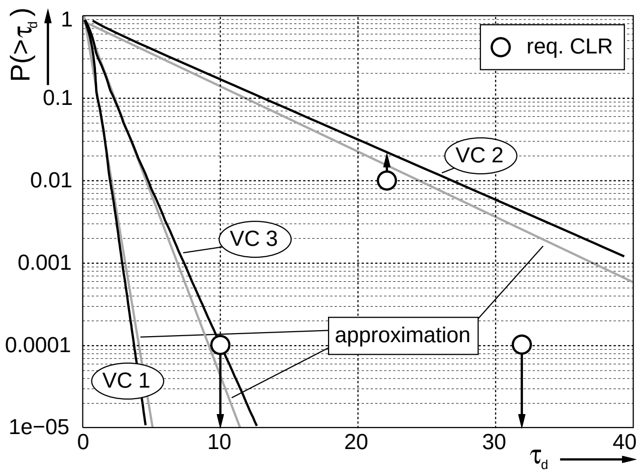
IV. Simulation of service disciplines for the ATM cell scheduler

VC	λ	τ_{dmax}/τ_{slot}	CLR
1	0.2	10	10^{-4}
2	0.45	22	10^{-2}
3	0.2	32	10^{-4}

TABLE I
Virtual connections in the test scenario

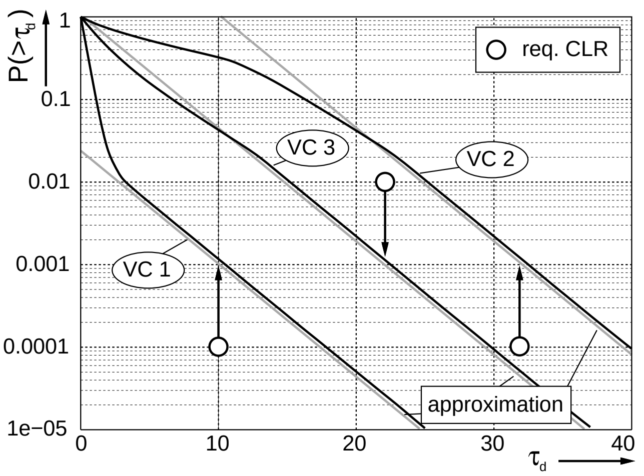
The approximations made for the complementary DF (4) as well as the ORU parametrization in section 2 are validated using stochastic simulations. A test scenario with three VCs

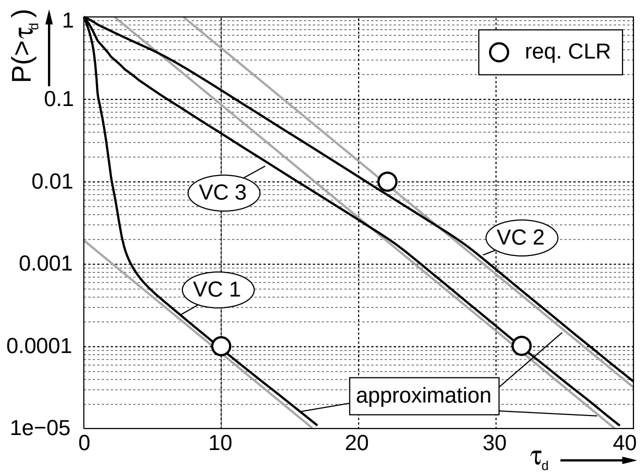




CLR with FCFS		
VC	approx.	simulated
1	$4.3 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
2	$9.1 \cdot 10^{-4}$	$9.9 \cdot 10^{-4}$
3	$3.7 \cdot 10^{-5}$	$4.3 \cdot 10^{-5}$

CLR with SP			
VC	Prio.	approx.	simulated
1	1	$4.5 \cdot 10^{-10}$	0
2	3	$1.6 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$
3	2	$9.5 \cdot 10^{-15}$	0





CLR - EDD		
VC	approx.	simulated
1	$1.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
2	$1.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
3	$1.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$

CLR - ORU			
VC	ORU	approx.	simulated
1	10	$8.1 \cdot 10^{-5}$	$9.4 \cdot 10^{-5}$
2	37	$9.3 \cdot 10^{-3}$	$7.1 \cdot 10^{-3}$
3	32	$8.1 \cdot 10^{-5}$	$9.5 \cdot 10^{-5}$

Fig. 3: Complementary DF of the cell delays for different service disciplines. The circles indicate the requested CLR.

is applied, cf. Tab. I. The values for cell delay and CLR are chosen to enable the gathering of stochastically proofed results in an acceptable run time of the simulation. The length of a simulation run is automatically controlled by the LRE algorithm [16] 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 5%.

A. Simulation of the M/G/1 queueing system

In Fig. 3 the ability to fulfil the CLR requirements is compared for the service disciplines First-Come-First-Serve (FCFS), Static Priorities (SP), Earliest-Due-Date-First (EDD) and Optimized-Relative-Urgency (ORU).

FCFS Using FCFS the complementary cell delay DF of all VCs is the same because no differentiation between connections is made. Thus, the requirements of VCs with

VC	model	λ	τ_{dmax}	CLR	ORU
1	video	0.2	100	10^{-4}	100.0
2	Poisson	0.45	30	10^{-2}	75.28
3	Poisson	0.3	300	10^{-5}	277.4

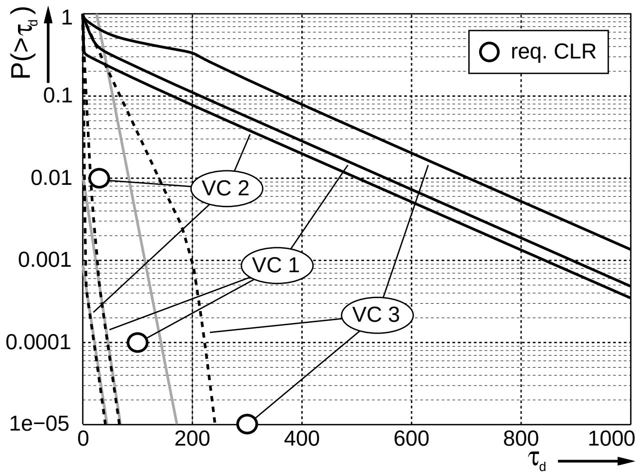


Fig. 4: Impact of using a video traffic source model instead of Markovian model for VC 1 with the ORU service discipline

VC	λ	τ_{dmax}	ORU	CLR		
				required	no discard	discard
1	0.15	20	27.3	10^{-2}	$6.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
2	0.2	25	32.3	10^{-2}	$6.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
3	0.1	10	2.7	10^{-4}	$9.0 \cdot 10^{-5}$	$< 10^{-6}$
4	0.1	15	7.7	10^{-4}	$8.9 \cdot 10^{-5}$	$< 10^{-6}$
5	0.1	12	4.7	10^{-4}	$9.2 \cdot 10^{-5}$	$< 10^{-6}$
6	0.05	40	32.7	10^{-4}	$9.0 \cdot 10^{-5}$	$< 10^{-6}$
7	0.15	35	35	10^{-3}	$9.2 \cdot 10^{-4}$	$1.9 \cdot 10^{-6}$

TABLE II: Scenario for analyse impact of discarding delayed cells. CLRs are compared with and without discarding.

shorter τ_{dmax} and higher CLR demands (VC 1) are difficult to meet, while less critical connections (VC 3) are preferred more than necessary.

Static priorities Static priorities usually do not offer enough flexibility to handle different requirements of virtual connections. The risk of creating great gaps between the CLR of different priority classes increases with the diversity of requirements. In the test scenario VC1 and VC3 are granted better CLRs than require. The achieved CLR of VC 2, however, is not sufficient.

EDD Using the EDD service discipline the same CLR for all VCs is obtained. As proved by analyses, individual requirements of VCs are not considered. VCs with the more critical constraints (VC1) experience a violation of their negotiated QoS.

ORU Only the ORU scheduling policy is able to fulfil the individual CLR requirements of all VCs. According to the analysis the assignment of resources to connections is performed in a „fair" way.

The simulation results show that the approximation of the cell delay DF (4) is particularly valid for long delays and high quantiles of the DF. The quality of the approximation is sufficient for comparing the different service strategies. This comparison shows that the Relative Urgency Strategy with parametrization of the urgencies according to the QoS constraints of the VCs (ORU) is able to control the statistical multiplexing of ATM cells, thus satisfying the needs of each individual VC.

B. Impacts of more realistic models for ATM traffic sources

Instead of using a Markovian source model for all ATM sources we now show the impact of modelling one virtual connection with a video source generating VBR ATM traffic. It is modelled with a autoregressive process according to [17]. The distance between two bursts (video images) is equal to 100. Within a burst one cell per transmission slot is generated.

The impact of this video model on the cell delays is analysed with the scenario from Fig. 4, where VC 1 is modelled with a video source.

In Fig. 4 the large error of the approximation is visualized. Due to the high variance of the data rate of the video source, the system is highly overloaded and CRLs cannot be guaranteed. This, however, does not affect the ability of the ORU service discipline to handle the virtual connections

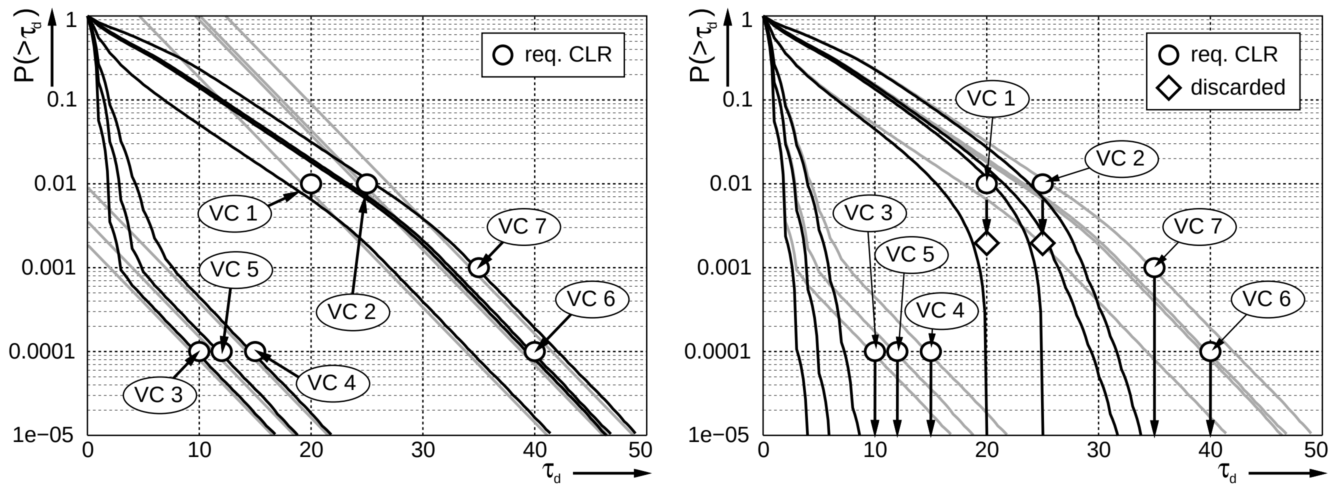


Fig. 5: Impacts of a selective discarding algorithm for delayed cells

according to their priorities. Thus, if the CAC ensures that the CLRs of all connections do not exceed their limits, the ORU priority strategy is an appropriate policy to fulfil the individual CLR requirements of the connections. However, the CAC needs similar models as the ATM cell scheduler.

C. Impacts of a cell discarding algorithm on cell delays

In the previous analysis the assumption was made that all cells including the delayed ones are transmitted. However, discarding old ATM cells before transmission can 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.

The selective discarding of delayed cells is analysed with the scenario in Table II.

The simulation results impressively show the positive impacts of discarding ATM cells. Therefore, the use of cell discarding as a part of the schedulers activities to enforce QoS is strongly recommended.

V. CONCLUSION

The analysis of service strategies for scheduling the transmission of ATM cells over an air interface with a multiplex rate of 20 Mbit/s have shown the importance of employing deadline oriented service strategies. With simpler strategies like static priorities or First-Come-First-Serve, real-time application cannot be supported with sufficient Quality of Service. The execution of deadline oriented service strategies in a real distributed system by an appropriate MAC protocol is subject of several publications. It has been shown, that advanced access methods can minimize the influence of transmitting capacity request messages over the uplink for informing the scheduler in the base station about the state of sending buffers in terminals [18].

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