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Analysis of a Rate-Based Control Policy with Delayed Feedback and Variable Bandwidth Availability

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Abstract

The investigation of feedback controls for telecommunication networks has recently gained considerable interest. The reason is the definition of a new ATM service category, the so-called Available Bit Rate service, whose primary goal is the economical support of applications with vague requirements for throughputs and delays.

One class of possible feedback controls is formed by the rate-based mechanisms. Feedback from the network switches to the end systems gives users the information necessary to appropriately adjust their transmission rates. This type of control has been investigated to some extent in the existing literature, assuming a constant transmission rate on a bottleneck link.

In this paper, we present a discrete-time analysis of a feedback control policy, taking into account a bottleneck link capacity that varies according to a general probability distribution. The control policy we look at belongs to the class of explicit rate control mechanisms considered for the Available Bit Rate service. We compute the buffer content and transmission rate distributions at appropriate time instants to investigate the influence of the variation of the bottleneck link capacity on the system performance.

1 Introduction

Recent advances in the development of B-ISDNs led to the definition of a fourth ATM service category, the so-called Available Bit Rate (ABR) service. Its primary goal is the economical support of applications with vague requirements for throughputs and delays, which are mainly data transmissions. This new service will systematically and dynamically allocate available bandwidth to the users by controlling the rate of offered traffic through feedback. To implement such a framework, a closed-loop feedback policy has been developed by the ATM Forum [1] operating on a rate-oriented basis.

A distinguishing feature of ABR sources is their ability to submit cells into the network at a variable but controlled rate, the Allowed Cell Rate (ACR). The ACR is initially set to the Initial Cell Rate (ICR) and is always bounded between the Minimum Cell Rate (MCR) and the Peak Cell Rate (PCR), which are negotiated at connection setup. It is controlled by the return of Resource Management (RM) cells, which are sent periodically by the source and looped back by the destination. The submission of an RM cell occurs typically after every $(N_{rm} - 1)$ user cells transmitted.

As the RM cells travel through the network, the switches provide information about their current congestion status by modifying the content of them. When an RM cell arrives back at the source, the source resets its ACR based on the information carried by the RM cell. If congestion is indicated, the source must decrease its ACR, otherwise it may increase its ACR by a fixed amount.

By implementing such a policy, network congestion is controlled or avoided, and the available bandwidth is used economically. A typical communication network implementing the ABR framework is presented in Figure 1.

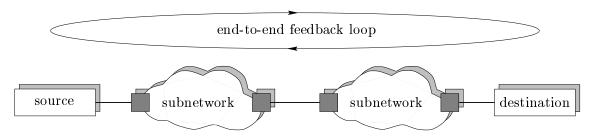


Figure 1: Implementation of the ABR service framework

Feedback controls for communication networks have been analyzed to some extent [6, 8, 16]. A large number of the papers deals with the modeling of the dynamical system behavior during steady-state. The dynamics, which occur due to the feedback delay, are an undesirable side effect [17, 18, 19]. Others investigate the dynamical behavior during initial and specific transient phases [5, 7]. Performance measures of interest are the convergence of the mechanism [9, 12, 14], the size of the switch buffers required to avoid cell losses [10, 13, 20, 22, 23], fairness properties [4], and the speed of the adaptation to changes of the system configuration [3, 11].

In almost all papers published on feedback control, the authors assume a fixed capacity available on the bottleneck link. However, looking at the ABR service category, the

capacity available for this type of service typically varies with time. This is caused, on the one hand, by the varying bandwidth demands of *Variable Bit Rate* (VBR) connections, and on the other hand, by the establishment and release of real-time connections, which have priority over ABR connections.

In this paper, we present a discrete-time analysis of a feedback control policy, taking into account a bottleneck link rate that varies stochastically. Therefore, we assume that the cells queued up before the bottleneck link are served according to a general service time distribution. The feedback policy investigated belongs to the class of explicit rate control mechanisms considered for the ABR service.

The paper is organized as follows. Section 2 presents the basic operation mode of the control mechanism and describes the model used for the analysis, which is outlined in Section 3. Numerical results to illustrate the accuracy of our algorithm and to analyze the system behavior are presented in Section 4. The paper concludes with a brief summary in Section 5.

2 Basic operation and model

Once the ABR connection is set up and the values for the ABR-specific parameters are identified, the source begins cell transmission. It is allowed to schedule cells with a rate up to the ACR, which is dynamically adjusted to the network load, as mentioned above. In the following we describe the operation mode of the *Explicit Rate* (ER) control analyzed in the next section.

A network switch signals congestion by modifying the content of the RM cells for those connections for which it is a bottleneck. It sets the *Congestion Indication* (CI) bit and decreases the rate signaled in the ER field to a value it can support. If the switch is in a non-congested state, the content of the RM cells remains unchanged.

At the return of an RM cell carrying positive feedback, i.e. no congestion was detected by the switches, the source may increase its ACR by a fixed increment $N_{rm} \cdot AIR$, but never exceeding the PCR. The RM cell frequency N_{rm} and the Additive Increase Rate (AIR) are determined at connection setup. Since the switches do not modify the RM cells as long as they are in a non-congested state, the ER value is equal to the PCR. If congestion is indicated, the source must decrease its ACR to the ER carried in the RM cells, but never below the MCR. A precise definition of the behavior of the Source End System (SES) and the Destination End System (DES) can be found in the ABR specification of the ATM Forum [2].

To investigate this feedback control by analysis, we model a single ABR connection as depicted in Figure 2. The SES and the DES communicate via a single network switch, which constitutes a bottleneck in forward direction. In backward direction, no congestion occurs. Congestion is detected by the switch when the buffer content exceeds an upper threshold B_H , and is regarded as terminated if the buffer content subsides to a lower threshold B_L . We assume that the switch transmits cells to the DES according to a general cell inter-departure time distribution $\mu(i)$.

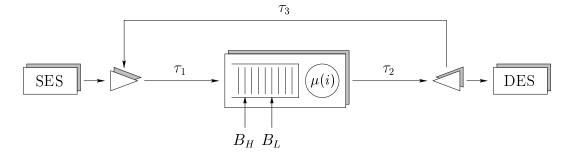


Figure 2: Model of a single ABR connection

The SES operates in a saturated condition, i.e. it always submits cells with the relevant ACR. The variables τ_1 and τ_2 denote the propagation delay between the SES and the switch, and between the switch and the DES, respectively. In backward direction, the propagation delay is given by $\tau_3 = \tau_1 + \tau_2$, resulting in a Round Trip Time (RTT) of $\tau = 2(\tau_1 + \tau_2)$.

Considering this configuration, the evolution of the ACR R(t) and the buffer content B(t) observed during steady state looks in principal as depicted in Figure 3.

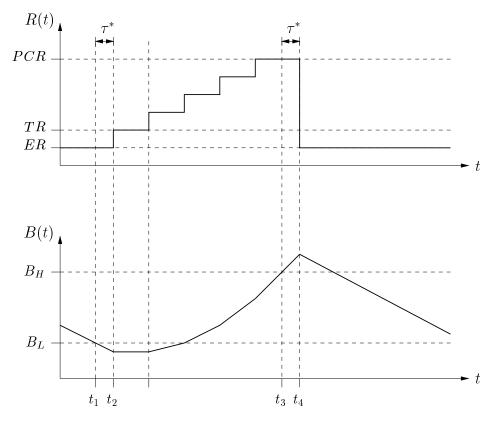


Figure 3: Evolution of the allowed rate R(t) and the buffer content B(t)

After a congested period has expired (t_1) , it takes a feedback delay of τ^* until the SES receives positive feedback from the network and starts to increase its ACR (t_2) . The ACR is increased at each return of a backward RM cell at the source (but never exceeding the PCR), as long as positive feedback is signaled (t_3) . If negative feedback is received, the

ACR is set to the ER computed by the switch (t_4) . Again, it takes a feedback delay of τ^* until the SES recognizes that the buffer content has exceeded B_H . We assume that the switch signals a constant ER during congested periods, lower than the mean cell transmission rate $TR = E[\mu(i)]$ on the bottleneck link.

Figure 3 shows a linear decrease and a step-wise linear increase of the buffer content. This would only be observed with a constant transmission rate on the bottleneck link. In our case, however, the increase and decrease rate of the buffer content varies with the transmission rate. Furthermore, the length of the periods between two increase steps of the ACR may vary considerably due to the stochastic server.

The following section presents an algorithm to derive distributions of the ACR and the buffer content at special time instants during steady-state. These distributions are used in Section 4 to investigate the system performance.

3 Performance analysis

Due to the slotted nature of the ATM environment, the modeling and analysis of mechanisms applied in ATM system is appropriately performed in the discrete-time domain. We first introduce a number of expressions used in our analysis.

The discrete convolution of the cell inter-departure time distribution $\mu(i)$ k times with itself is denoted by

$$\mu_k(i) = \underbrace{\mu(i) \star \cdots \star \mu(i)}_{k} \quad , \tag{1}$$

and the corresponding complementary distribution function is given by

$$\mu_k^c(i) = 1 - \sum_{j=0}^i \mu_k(j) \quad . \tag{2}$$

Furthermore, we denote the recurrence distribution of $\mu_k(i)$ by

$$\mu_k^r(i) = \frac{1}{\mathrm{E}[\mu_k(i)]} \cdot \mu_k^c(i) \quad , \tag{3}$$

and its corresponding complementary distribution function by

$$\mu_k^{rc}(i) = 1 - \sum_{j=0}^i \mu_k^r(j) \quad . \tag{4}$$

Since our model includes a stochastic process, the system state is expressed by the distribution of the buffer content $B_t(i)$ and the distribution of the ACR $R_t(i)$ at a given time

instant t. Thus, the probability that the buffer contains i cells at time t is given by $B_t(i)$. For the representation of the ACR, we use a mapping due to its non-integer nature. In the following, $R_t(i)$ corresponds to the rate

$$r(i) = (ER + i \cdot N_{rm} \cdot AIR) \quad . \tag{5}$$

The derivation of the distributions at the time instants t_1, \ldots, t_4 , cf. Figure 3 in Section 2, is outlined in the next four subsections. To simplify the description, we consider the ACR that was relevant τ_1 time units before t, i.e. we consider the rate at which the cells arrive at the switch at time t.

3.1 Distributions at the end of a congested period

We start with the distributions observed at the end of a congested period (t_1) , i.e. the time instant when the buffer content subsides to B_L .

3.1.1 Transmission rate distribution

As long as the switch is in the congested state, it signals an ER in the ER field of the RM cells, which is of course lower than the mean transmission rate TR. Thus, we obtain a deterministic transmission rate distribution $R_{t_1}(i)$, i.e.

$$R_{t_1}(i) = \delta(i) \quad , \tag{6}$$

where $\delta(\cdot)$ denotes the discrete-time Dirac impulse.

3.1.2 Buffer length distribution

The distribution of the buffer content is simply given by

$$B_{t_1}(i) = \delta(i - B_L) \quad . \tag{7}$$

3.2 Distributions at the end of an ER signaling phase

Next, we compute the system state distributions just before the SES receives the first positive feedback after congestion was terminated (t_2) . The period between t_1 and t_2 constitutes the feedback delay τ^* , which determines the dynamic system behavior.

3.2.1 Transmission rate distribution

At t_2 , the SES still transmits with the ER, i.e.

$$R_{t_2}(i) = \delta(i) \quad . \tag{8}$$

3.2.2 Buffer length distribution

For the computation of the buffer length distribution at t_2 , we are interested in the number of cells that arrive at the buffer and depart from the buffer respectively, during a given time interval t.

The probability $D_t(i)$ that i cells depart from the buffer within t time slots is given by

$$D_t(i) = \sum_{j=i}^t \mu_i(j) \cdot \mu_1^c(t-j) \qquad \text{for} \qquad t = 0, \dots, \infty \quad .$$
 (9)

Since the source still sends with the ER, we derive the probability $A_t(i)$ that i cells arrive at the buffer within t time slots by

$$A_t(i) = \delta(i - |ER \cdot t|) \qquad \text{for} \qquad t = 0, \dots, \infty \quad . \tag{10}$$

Consequently, the probability $H_t(i)$ that the buffer contains i cells after t time slots is

$$H_t(i) = \pi_0 \left[B_{t_1}(i) \star A_t(i) \star D_t(-i) \right] \qquad \text{for} \qquad t = 0, \dots, \infty \quad , \tag{11}$$

where $\pi_0[\cdot]$ denotes the operator defined in [21].

The total feedback delay τ^* consists of the RTT τ and the time it takes until an RM cell is served by the switch after congestion was terminated. By multiplying the distributions $H_t(i)$ with the probability that the total feedback delay is equal to t, we obtain the buffer length distribution at the end of an ER signaling phase, i.e.

$$B_{t_2}(i) = \sum_{t=\tau}^{\infty} \mu_{N_{rm}}^r(t-\tau) \cdot H_t(i) \quad . \tag{12}$$

3.3 Distributions at the end of a non-congested period

In this subsection, we present the derivation of the system state distributions when the buffer threshold B_H is exceeded (t_3) . From this time instant on, the switch starts to signal an ER and sets the CI bit in the RM cells.

3.3.1 Transmission rate distribution

As long as positive feedback is received from the switch, the ACR is step-wise increased by $N_{rm} \cdot AIR$, cf. Section 2. Therefore, we compute the buffer length distribution after every increase step to obtain the distribution for $R_{t_3}(i)$. We proceed analogously to the last subsection.

The probability $D_t(i)$ that i cells depart the buffer within t time slots is again determined by Equation (9). Since the ACR is constant between two steps, we obtain for the probability $A_t^k(i)$ that i cells arrive at the buffer within t time slots

$$A_t^k(i) = \delta(i - \lfloor (ER + k \cdot N_{rm} \cdot AIR) \cdot t \rfloor) \quad \text{for} \quad t = 0, \dots, \infty \quad ,$$
 (13)

if we are currently situated between the k-th and the (k+1)-th increase step.

Performing a convolution operation, we arrive at the probability $H_t^k(i)$ that the buffer contains i cells t time slots after the k-th increase step, i.e.

$$H_t^k(i) = \pi_0 \left[B_{t_2}^{k-1}(i) \star A_t^k(i) \star D_t(-i) \right] \quad \text{for} \quad t = 0, \dots, \infty \quad ,$$
 (14)

with $B_{t_2}^0(i) = B_{t_2}(i)$.

Consequently, the distribution of the buffer content $B_{t_2}^k(i)$ just before the (k+1)-th increase step is given by

$$B_{t_2}^k(i) = \sum_{t=N_{rm}}^{\infty} \mu_{N_{rm}}(t) \cdot H_t^k(i) \quad . \tag{15}$$

To derive the probability that the ACR at the end of a non-congested period is equal to the rate corresponding to $R_{t_3}(i)$, we carry out the following summation

$$R_{t_3}(i) = \sum_{j=B_H}^{\infty} B_{t_2}^i(j) \cdot \left(1 - \sum_{l=0}^{i-1} R_{t_3}(l)\right)$$
 (16)

3.3.2 Buffer length distribution

Clearly, the buffer length distribution is given by

$$B_{t_3}(i) = \delta(i - B_H) \quad . \tag{17}$$

3.4 Distributions at the end of an increase phase

The last subsection deals with the computation of the system state distributions observed just before the ACR is decreased to the ER (t_4) , i.e. the time instant when the first negative feedback is received. At this time instant, the buffer content reaches its maximum value in a cycle consisting of one decrease and one increase phase.

3.4.1 Transmission rate distribution

The distribution of the ACR $R_{t_4}(i)$ can be computed similarly to the last subsection. Since we are primarily interested in the buffer length distribution, we omit the description.

3.4.2 Buffer length distribution

To obtain the distribution of the buffer content, we first compute the distribution for the number of cells that arrive at the buffer and depart from the buffer respectively, during a given time interval t.

For the departures we again refer to Equation (9), which is used to calculate the probability $D_t(i)$ that i cells depart the buffer within t time slots. The derivation of the distributions for the arrivals is more complex. Since the ACR is not a deterministic value at the time instant t_3 , we first need to compute the conditional probabilities $A_t^j(i)$ that i cells arrive at the buffer within t time slots if the initial ACR is equal to the rate corresponding to $R_{t_3}(j)$ (cf. Equation (5)).

If we consider further increases of the ACR, which may occur during the feedback delay, the probabilities $A_t^j(i)$ are given by

$$A_{t}^{j}(i) = \mu_{N_{rm}}^{rc}(t) \cdot \delta(i - \lfloor r(j) \cdot t \rfloor) + \delta(i - \lfloor r(j) \cdot t \rfloor) + \sum_{t_{1}=0}^{t} \mu_{N_{rm}}^{r}(t_{1}) \cdot \mu_{N_{rm}}^{c}(t - \sum_{k=1}^{1} t_{k}) \cdot \delta(i - \lfloor r(j) \cdot t_{1} + r(j+1) \cdot (t-t_{1}) \rfloor) + \sum_{t_{1}=0}^{t-N_{rm}} \sum_{t_{1}=N_{rm}}^{t-t_{1}} \mu_{N_{rm}}^{r}(t_{1}) \cdot \mu_{N_{rm}}^{r}(t_{2}) \cdot \mu_{N_{rm}}^{c}(t - \sum_{k=1}^{2} t_{k}) \cdot \delta(i - \lfloor r(j) \cdot t_{1} + r(j+1) \cdot t_{2} + r(j+2) \cdot (t-t_{2} - t_{1}) \rfloor) + \vdots$$

$$\vdots$$
(18)

The conditional distributions are weighted by the probability of the initial ACRs to obtain the probability $A_t(i)$ that i cells arrive at the buffer within t time slots.

$$A_t(i) = \sum_{j=0}^{\infty} R_{t_3}(j) \cdot A_t^j(i)$$
 for $t = 0, \dots, \infty$. (19)

Finally, the buffer length distribution observed after t time slots $H_t(i)$ is given by

$$H_t(i) = \pi_0 \left[Q_{t_3}(i) \star A_t(i) \star D_t(-i) \right] \qquad \text{for} \qquad t = 0, \dots, \infty \quad , \tag{20}$$

and the buffer length distribution just before the ACR decreases to the ER is obtained by

$$Q_{t_4}(i) = \sum_{t=\tau}^{\infty} \mu_{N_{rm}}^r(t-\tau) \cdot H_t(i) \quad , \tag{21}$$

considering the feedback delay τ^* (cf. Subsection 3.2.2).

4 Numerical results

The discrete-time analysis presented in the last section is only of an approximate nature due to synchronization and timing effects occurring in the real system and neglected in our analysis. Therefore, we first study the accuracy of our algorithm by comparing the buffer length distributions computed analytically with those obtained by simulation. For this purpose, we used the following system configuration:

- the physical layer is based on a SONET STS-3c system (SDH), i.e. the links have a transmission capacity of 155 Mbps,
- the propagation delays between the network components are $\tau_1 = 0.04 \text{ ms}$, $\tau_2 = 0.04 \text{ ms}$ and $\tau_3 = 0.08 \text{ ms}$, resulting in a round trip distance of approximately 30 km,
- the buffer thresholds are set to $B_L = 128$ and $B_H = 256$ cells,
- the cell inter-departure time distribution $\mu(i)$ is geometric with a mean of 4.0, which corresponds to 25% of the link capacity,
- the RM cell frequency is set to $N_{rm} = 32$,
- the PCR is equal to the link capacity (155 Mbps),
- the ER equals 20% of the link capacity,
- and the AIR is set to 0.1% of the link capacity.

Figure 4 shows a good agreement between the buffer length distributions $Q_{t_2}(i)$ measured at the end of an ER signaling phase. The main portion of the distribution is located below the threshold B_L , since the cell arrival rate during the feedback delay is lower than the mean transmission rate over the bottleneck link. Theoretically, the mean buffer length at t_2 is computed by

$$\bar{B}_{t_2} = B_L + (ER - TR) \cdot \bar{\tau}^* \approx 122.2 \quad ,$$
 (22)

where $\bar{\tau}^*$ denotes the mean feedback delay. Comparing \bar{B}_{t_2} with the result from simulation and from our analysis, we also observe a good agreement, cf. Table 1.

Measure	Simulation	Analysis
mean value	122.6	121.9
10^{-3} quantile	107	103
$1 - 10^{-3}$ quantile	136	135

Table 1: Accuracy of the mean and the 10^{-3} quantiles

Furthermore, Table 1 shows that both 10^{-3} quantiles are well approximated.

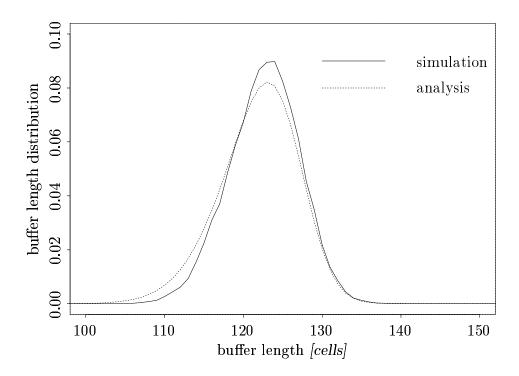


Figure 4: Buffer length distribution observed at the end of an ER signaling phase

The next figure presents the buffer length distribution noticed after an increase phase, i.e. at the time instant t_4 . Again, a good agreement between simulation and analytical results is observed, cf. Figure 5.

The main portion of the probability distribution is now located beyond B_H , since the cell arrival rate during the feedback delay is higher than the mean transmission rate over the bottleneck link. The theoretical value for the mean content of the buffer at this time instant can not be computed in such an easy way as before. The reason for that is the step-wise increase of the ACR during non-congested periods, which may lead to different values of the ACR when congestion is detected.

Table 2 compares the mean and the 10^{-3} quantiles obtained by simulation with those computed with our analysis. As already mentioned, the buffer achieves its maximum length within a cycle at t_4 .

Measure	Simulation	Analysis
mean value	286.6	287.7
10^{-3} quantile	259	261
$1 - 10^{-3}$ quantile	334	329

Table 2: Accuracy of the mean and the 10^{-3} quantiles

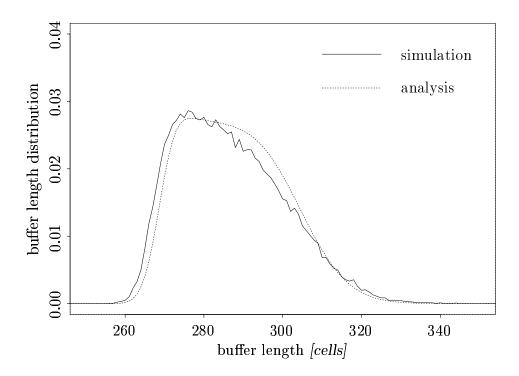


Figure 5: Buffer length distribution observed after an increase phase

After checking the accuracy of our analysis, we investigate the influence of various system parameters on the buffer length distribution. The first parameter we look at is the coefficient of variation of the cell inter-departure time distribution $\mu(i)$. Figure 6 shows the mean (solid lines) and the 10^{-3} quantiles (dotted lines) of the buffer length distributions at t_2 and t_4 as functions of the coefficient of variation. The cell inter-departure times are negative-binomially distributed with a mean equal to 4.0 and the other system parameters are set as described at the beginning of this section.

First, we observe that the mean variation of the queue length distributions increases with the coefficient of variation, in particular for the distribution observed at t_4 . While the mean queue length at t_4 remains almost constant, it increases slowly and almost linearly if measured at t_2 . For comparison, the queue length observed with a deterministic cell transmission rate are 119 cells at t_2 and 303 cells at t_4 . Thus, the variation of the bottleneck link capacity has only a minor influence on the mean queue length observed at t_2 and t_4 . The 10^{-3} quantiles, however, deviate from the mean by typically 10% to 20%.

The influence of the RTT on the system performance is studied in Figure 7. Using a negative-binomial distribution as before with a coefficient of variation equal to 1.0, we varied the round trip distance, i.e. twice the distance between the SES and the DES, from 10 to $100 \ km$. Figure 7 indicates a weak linear dependency of the mean and the quantiles for both distributions. This observation was already made in [20] for a bottleneck link having a constant rate.

In the next two figures, the mean and the quantiles are plotted as functions of the ER and the AIR respectively. For the ER, cf. Figure 8, we again observe a weak linear dependency of the mean and the quantiles measured at t_2 . The buffer length distribution after an increase phase (t_4) is hardly influenced by this parameter.

In contrast, the buffer length distribution observed at t_2 remains constant if we vary the AIR, as depicted in Figure 9. In this case, the mean and the quantiles measured at t_4 show a fast increase with the AIR until it is large enough to achieve the PCR before congestion is detected.

5 Conclusion

In this paper, we presented an analysis of a feedback control, which is employed to support the Available Bit Rate service in ATM networks. The control policy belongs to the class of explicit rate control mechanisms suggested by the ATM Forum.

Our algorithm operates in the discrete-time domain and takes into account a bottleneck link capacity that varies according to a general probability distribution. Such variations may occur due to the higher priority of real-time ATM connections. To investigate the influence of the capacity variations on the system performance, we look at buffer length distributions at specific time instants.

The numerical results obtained with our algorithm, which is of an approximate nature, show a high accuracy for the mean and for the quantiles of the distributions. We discovered a weak linear dependency of the mean and the quantiles on almost all system parameters. This behavior indicates a stable operation of this feedback control mechanism in real ATM networks.

Acknowledgment

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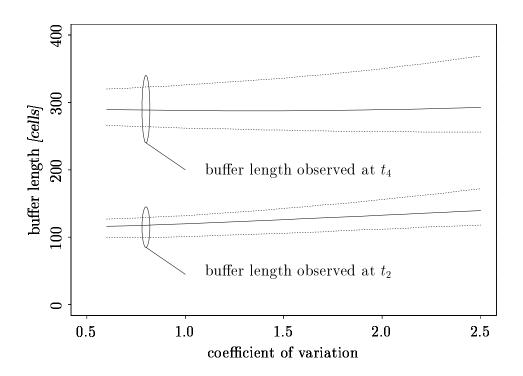


Figure 6: Dependency of the buffer length on the coefficient of variation

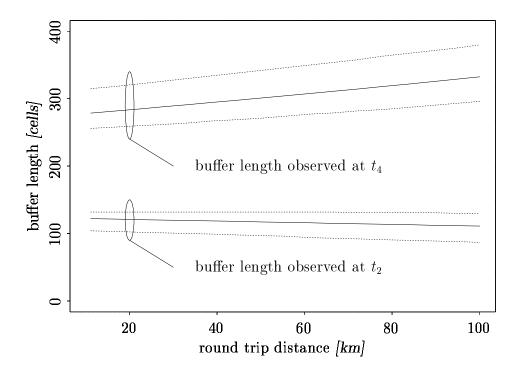


Figure 7: Linear dependency of the buffer length on the RTT

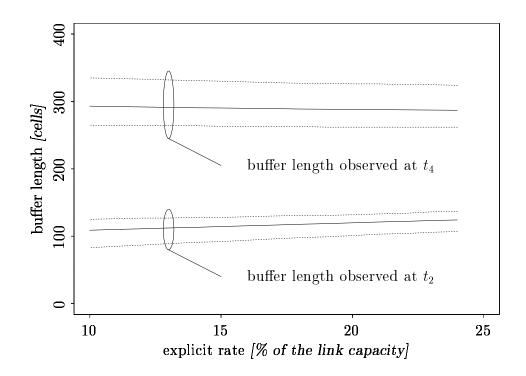


Figure 8: Linear dependency of the buffer length on the ER

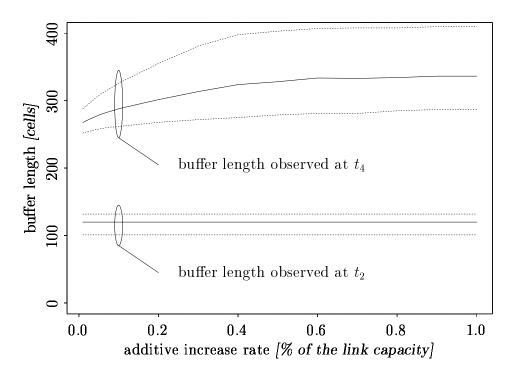


Figure 9: Dependency of the buffer length on the AIR

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