University of Würzburg
Institute of Computer Science
Research Report Series

A Decomposition Approach for User-Network Interface Modeling in ATM Networks

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Report No. 169 April 1997

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Abstract

In ATM networks, the user-network interface configuration strongly influences the performance of the network and determines the functional complexity of network elements. A main issue, for example, is the location of traffic shaping devices at the private and public user-network interface. Traffic shaping may be performed by customer premises equipment or by ATM switches itself.

This paper presents a decomposition approach for user-network interface modeling. The analytical approach allows to investigate the effectiveness of traffic shaping with respect to the statistical multiplexing gain obtained at the network ingress.

Keywords

ATM, Connection Traffic Descriptor, Multiplexer, Performance Analysis, Traffic Shaping.

1 Introduction

In the current state of ATM interface and network operation standardization, *User-Network Interface* (UNI) functionalities are fixed only for the most important components [14, 22]. The location and implementation of traffic control functions such as shaping mechanisms is left to operators and manufacturers of ATM equipment. It is a network operator's choice to determine whether and where these controls are performed. As an example, a network operator may choose to perform traffic shaping in conjunction with suitable *Usage Parameter Control* (UPC) or cell scheduling on separate or aggregate cell flows. Generally, the options available to implement traffic shaping are the following:

- Traffic shaping may be performed at the customer premises equipment or the end systems itself in order to ensure that the cells generated by the user are conforming to the negotiated traffic descriptors at the UNI. In this case, system complexity with regard to traffic shaping is located in the end systems, reducing the functional complexity of network nodes.
- In contrast, traffic may be shaped at the ingress of the network and resources are allocated according to the traffic characteristics achieved by shaping. This sort of traffic shaping is typically combined with cell scheduling or UPC functions located at the network ingress and increases the functional complexity of network nodes.

In this paper, the effectiveness of traffic shaping at the UNI is investigated, aiming at the enhancement of statistical multiplexing gain at the network ingress. Depending on the way traffic is shaped, buffer requirements and cell loss can be reduced. Of course, shaping can only be performed to a certain extent due to delay objectives agreed on in the traffic contract. Thus, a trade-off between delay and statistical multiplexing gain occurs for real-time connections of the CBR and VBR service category.

The organization of the paper is as follows. Section 2 presents the functional configuration of the UNI model considered. For analyzing the performance of this model, a decomposition approach is applied, which is outlined in Section 3. The approach was selected in order to be able to investigate realistic network scenarios with a large number of connections. Section 4 discusses the accuracy of the approach and presents numerical examples. The paper concludes with final remarks in Section 5.

2 User-Network Interface Model

ATM technology can be used within both private networking products and public networks such as the B-ISDN. In recognition of this fact, two distinct forms of the UNI are defined [22]. The public UNI is typically used to interconnect ATM users with ATM switches deployed in a public service provider's network. It is modeled after the B-ISDN UNI defined in ITU Recommendations and ANSI standards [13]. In contrast, the private UNI is an interface optimized for local campuses or applications and interconnects ATM users with switches that are managed as part of the same corporate network. Alternative physical layer interfaces for short distance links with reduced operation and management complexity are provided. Thus, the primary distinction between these two classes is physical reach, besides of some minor functionality differences due to the application requirements associated with each of these interfaces. A general configuration of the UNI is depicted in Figure 1. The ATM user devices may either be intermediate systems — such as IP routers — that encapsulate data into ATM cells, or private ATM equipment using a public network ATM service for the transfer of ATM cells. In the remainder of this paper, the term “UNI” refers to either the private or the public form of the interface.

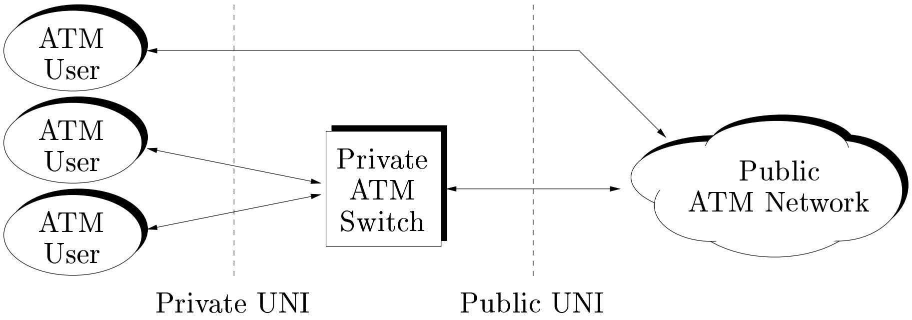


Figure 1: *Implementations of the ATM UNI*

In order to obtain a better network efficiency while meeting the QoS objectives, traffic shaping can be applied to achieve a desired modification of the traffic characteristics of a cell stream. Examples of traffic shaping are peak cell rate reduction, burst length limitation, and reduction of *Cell Delay Variation* (CDV) by suitably spacing cells in time. A distinct algorithm for traffic shaping is not specified in the standards documents [14, 22]. Common methods are cell spacing and dual cell spacing as defined in [4] and [20], respectively.

Depending on the way traffic is shaped, buffer requirements and cell loss can be reduced at the network ingress. However, the trade-off between costs for implementing shaping devices and the resulting multiplexing gain has to be evaluated carefully. Furthermore, shaping can only be performed up to a certain extend due to delay constraints given by applications on top.

To assess the efficiency of traffic shaping at the UNI, appropriate system modeling is required. The analysis presented in this paper is based on the traffic model depicted in Figure 2 and is primarily concerned with cell level performance. Cell streams of a number of traffic sources N — represented by arrival processes following general distributions (G) — are shaped individually before they are multiplexed at the UNI. Each source and the corresponding shaping device are assumed to be components of a single ATM end system, called ATM user in Figure 1. The shaper performs peak cell rate reduction and

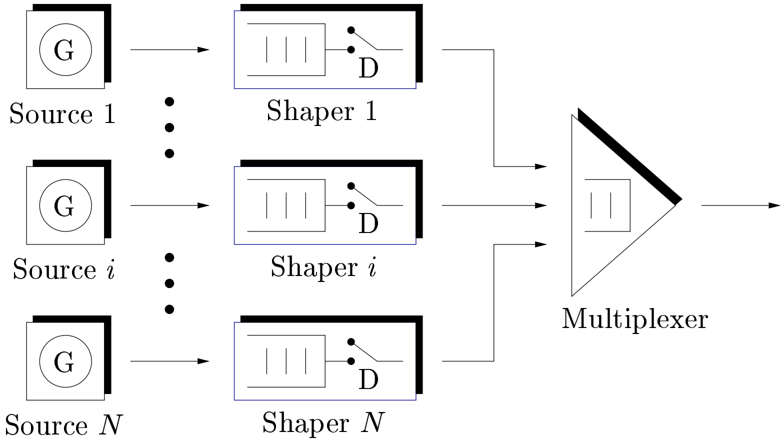


Figure 2: *Model of the user-network interface*

its buffer size is limited to a fixed value. Cells which would have to be queued in excess are discarded. The buffer located in the ATM multiplexer is also of finite size and operates according to the FIFO discipline. Consequently, cell loss may occur at the multiplexer, too.

In the next section, a decomposition approach for analyzing the UNI model depicted in Figure 2 is presented. The approach shows a reasonable accuracy and is of a low numerical complexity, which allows to investigate realistic scenarios with a large number of traffic sources.

3 Decomposition Approach

During the first phase of developing ATM equipment, there have been a number of simulation studies to investigate the queueing behavior of UNI models similar to the one shown in Figure 2 (cf. [9, 16]). The main drawback with simulation is its inability to produce reliable results for low cell loss rates, which are typical in ATM environments. For this reason, simulation studies usually give results for loss rates larger than 10^{-4} and extrapolation techniques are used to estimate smaller rates. However, the reliability of extrapolations is not easily verified.

In [18], the UNI model presented above is analyzed for batch arrivals as a whole applying a spectral expansion method for Markov modulated processes. The results obtained are of an exact nature, however, the numerical complexity is high. Thus, the application is limited to systems with a small number of sources. Since the number of active connections is typically large in ATM networks, the approach is unsuitable for studying the effectiveness of traffic shaping at the UNI.

A common method for analyzing complex queueing systems while expending reasonable numerical efforts is the use of decomposition approaches. Functional components of the system are analyzed individually and independently of other components, and the results derived are used for input to the analysis of other system components. For decomposition approaches, the description of interface processes strongly determines the accuracy of the final results.

The use of the cell inter-departure times of the traffic shapers is, for example, a possible approach to approximate the superposition of cell streams from a number of shapers by a mathematical tractable process. The composite system can then be analyzed using a queueing model or stochastic fluid-flow model. In [7], the shaper output process is analyzed and approximated by a Markov-modulated fluid source, which is able to capture correlation in the output process. However, the numerical complexity of this method is still high and does not allow to consider cell-scale queueing performance.

Another approach is to characterize the shaper output as a renewal process [19]. By analyzing a multiplexer model where the input traffic is described by the superposition of renewal processes, approximate cell scale measures can be derived. Despite not modeling the correlation structure of the real process, the numerical complexity for solving the multiplexer model is high and only tractable for a small number of traffic sources.

Since the numerical complexity of a decomposition approach for the UNI model depicted in Figure 2 is mainly determined by the analysis of the ATM multiplexer, a more simple description of the interface process is required in order to deal with a large number of traffic sources. An efficient analysis of ATM multiplexers concentrating periodic sources is outlined in [5]. Using combinatory methods, the cell loss rate is derived for the discrete-time $N*D/D/1-K$ model, assuming that the cell inter-arrival times for each source are multiples of a time slot. Extensions and generalizations of this method can be found in [10, 11].

The main drawback of this approach is its numerical instability for larger numbers of sources and the restriction to periodic input traffic. Busy periods of the shaper can be reasonably modeled, but larger inter-emission intervals which occur during idle periods can not be considered. In general, the shaper output follows an on/off-process with periodic departures during on-periods. Nearly deterministic inter-emission times are observed only when the shaper operates under high load. In this case, the assumption of a periodic inter-departure process involves just a minor error.

In this paper, the following approximation is applied to investigate traffic scenarios where the spacer operates under moderate load. Instead of considering the minimum inter-cell distance enforced by the shaper for defining the periodic input process, the mean cell inter-departure time is used. Thus, the characteristics of the interface process solely depend on the intensity of the traffic stream departing the shaper, while assuming a deterministic traffic pattern. Due to the non-integer nature of the mean inter-cell times obtained with this approach, the analysis presented in [5] is not longer applicable. A solution for the continuous-time $N*D/D/1-\infty$ model is presented in [21], based on the Beneš approach [2] . It allows to consider periodic streams with periods of arbitrary length, is numerically stable, and has a low computational complexity. The cell loss rate in a finite buffer can be approximated by the tail behavior of the infinite buffer model.

Several other authors used the Beneš approach for modeling ATM multiplexers. The influence of bursty traffic and on/off-sources is studied in [6] and [8]. The authors consider, however, back-to-back cell arrivals, which makes their results useless with respect to the interface process defined above. Other extensions of the approach outlined in [21] are presented in [1, 3, 15, 17]. These papers discuss approximate solutions for non-renewal arrival processes which have a bursty nature or consider heterogeneous traffic scenarios. Due to the complexity and approximation uncertainties involved in these approaches respectively, the findings can not be applied for studying the effectiveness of traffic shaping. Thus, the decomposition approach based on the analysis presented in [21] is the most promising alternative and is investigated in the following.

To analyze the traffic shaper independently of the multiplexing component, a wide variety of approaches can be applied. Knowing the mean cell inter-arrival time $\mathrm{E}[A_s]$ at the shaper — which corresponds to the mean cell inter-generation time of the source — and the corresponding cell loss rate p_s, the mean cell inter-departure time $\mathrm{E}[D_s]$ is obtained by

$$\mathrm{E}[D_s] \quad = \quad \mathrm{E}[A_s] \cdot \frac{1}{1 - p_s} \quad . \tag{1}$$

Therefore, the determination of the cell loss rate observed at the traffic shaper is sufficient for the approach. Algorithms of low complexity which allow to determine the exact cell loss rate for renewal and on/off-processes can be found, for example, in [12] and [19], respectively.

In the next section, numerical examples are presented to discuss the accuracy of the decomposition approach and investigate the effectiveness of traffic shaping with respect to the statistical multiplexing gain obtained at the network ingress.

4 System Performance

4.1 Approximation Accuracy

Decomposition approaches generally provide approximate results of the system performance. As mentioned, the modeling of the interface processes used to combine the analyses of individual system components primarily determines the degree of accuracy. The more detailed these processes are modeled, the more accurate the results are. However, the numerical complexity increases in general with the description detail.

The decomposition approach described above involves two approximation steps:

- The output process of each shaping device is described by its intensity only. Thus, correlation structures are not modeled and consequently, the performance regarding cell loss p_M and cell delay $\bar{d}_M$ at the multiplexer is overestimated if the analysis of the multiplexer component is of an exact nature.

- The cell loss rate at the multiplexer is approximated by the tail behavior of the $N * D/D/1 - \infty$ queueing model. This approximation technique underestimates the system performance.

Since both approximation steps are combined, no quantitative statements about the accuracy of the approach can be given. However, qualitative statements are possible.

If the number of traffic sources N increases, correlation structures in the shaper output process have a decreasing influence on the system performance. The reason is the smoothing effect at the multiplexer buffer which becomes stronger when concentrating larger numbers of traffic streams. Thus, a large number of sources — as typical for ATM environments — positively influences the accuracy by reducing the tendency to overestimate the multiplexer performance.

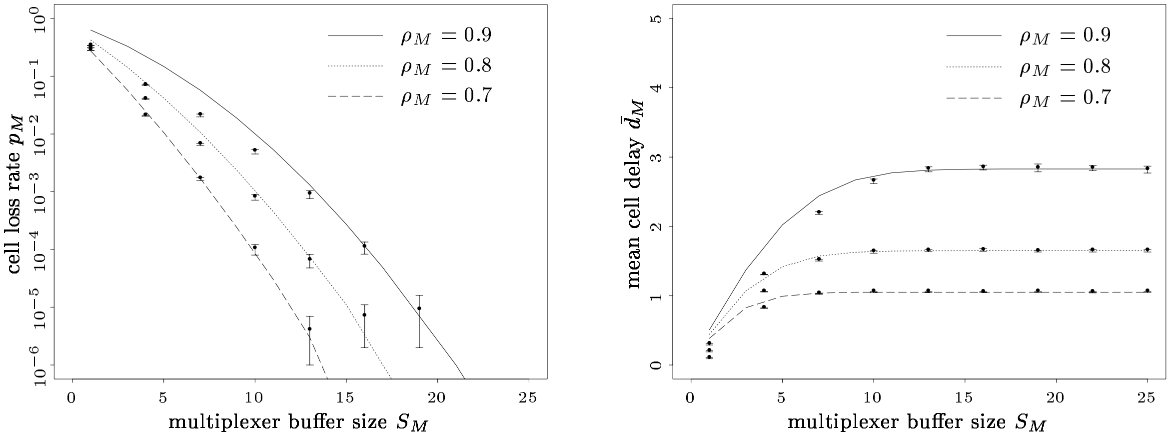
Shaping devices which operate at high loads ρ_S and are equipped with large buffers of size S_S also affect the accuracy in a positive manner. The higher a shaper is loaded and the more memory is available for the queueing of cells, the smoother the output process is [4]. Therefore, less information is lost by modeling the shaper output solely by its intensity and the tendency to overestimate the performance of the multiplexer becomes less. In real systems, the shaper load ρ_S is typically high in order to reduce the peak cell rate as much as possible, while the buffer size S_S has to be large enough to avoid cell loss.

Finally, the configuration of the multiplexer determines the accuracy of the decomposition approach. Since the cell loss rate — and also the mean cell delay — at the multiplexer is approximated by the tail behavior of the corresponding infinite queueing system, the performance is generally underestimated. This effect is less distinctive if the multiplexer load ρ_M is low, the buffer size S_M is large, and consequently the loss rate p_M is small. In real ATM networks, the target load is below $\rho_M = 0.9$ and the switch buffers available typically accommodate a few hundred of cells.

In the remaining part of this section numerical results derived by simulation and the decomposition approach are discussed in order to assess the approximation accuracy and study the effectiveness of traffic shaping at the UNI.

4.2 Numerical Examples

The first example depicted in Figure 3 shows the influence of the multiplexer buffer size S_M on the system performance for different loads ρ_M and homogeneous sources. Each of the $N = 100$ traffic sources generates cells according to a geometric distribution. The shaper enforces a minimum inter-cell distance of $T = 100$ cells and the buffer associated is large enough to guarantee a cell loss rate of $p_S < 10^{-4}$. As expected, the cell loss rate



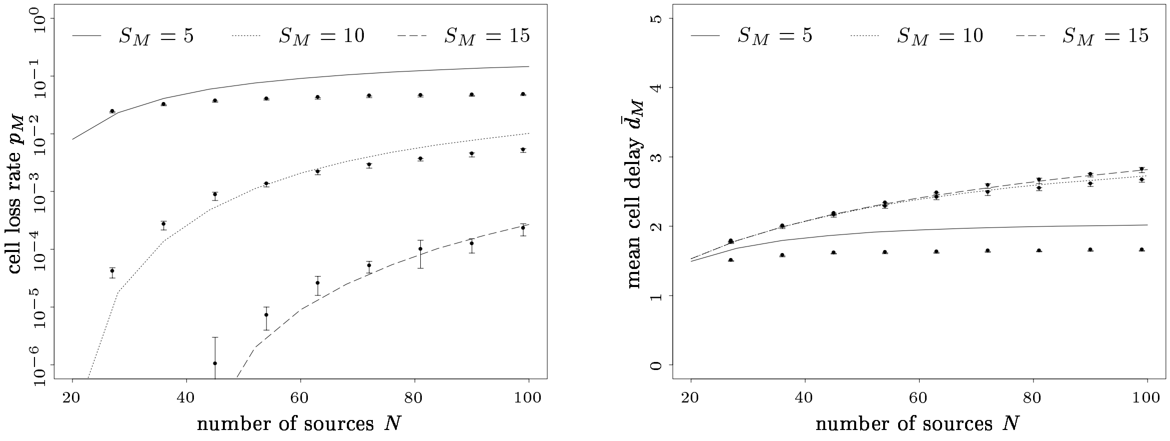
(a) *Cell loss performance*

(b) *Delay performance*

Figure 3: *Influence of the multiplexer buffer size* S_M

p_M decreases and the mean cell delay $\bar{d}_M$ increases with the buffer size at the multiplexer. For all loads ρ_M, the mean delay remains already constant for relatively small buffers. Regarding the approximation accuracy, the considerations and estimations made at the beginning of this sections are confirmed. The analytical results presented in both Figures 3(a) and 3(b) become more accurate for low loads ρ_M and large buffer sizes S_M.

Figure 4 illustrates the system performance in dependence of the number of homogeneous sources N. For a constant multiplexer load of $\rho_M = 0.9$ and irrespective of the buffer size S_M, the performance becomes worse when the number of traffic sources increases. Despite a constant load ρ_M, which is obtained by adjusting the cell-arrival process and



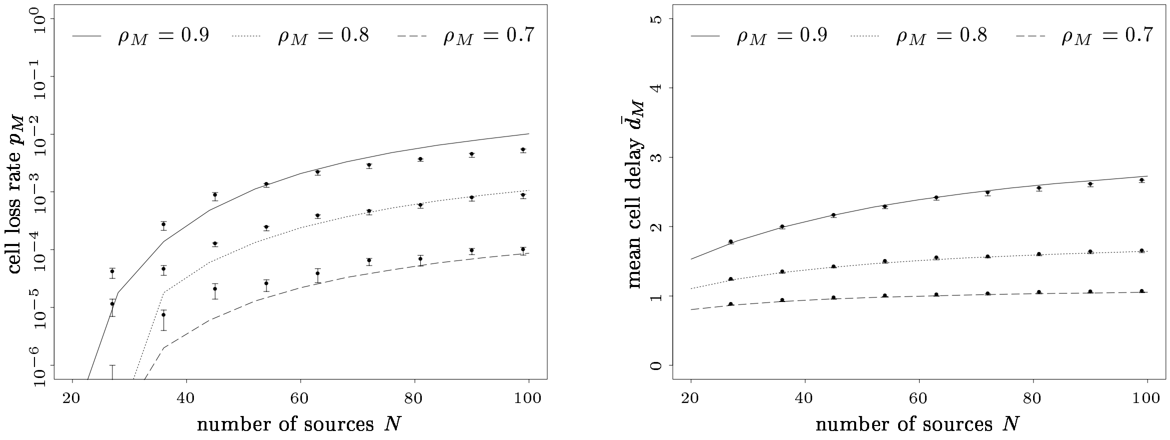
(a) *Cell loss performance*

(b) *Delay performance*

Figure 4: *Performance degradation for increasing numbers of sources N*

spacing interval T accordingly, the multiplexer performance is strongly affected by the number of sources. Regarding the accuracy of the decomposition approach, the tendency to underestimate the system performance — i.e. overestimating cell loss rate and mean cell delay — for small buffers and high loss rates at the multiplexer is clearly demonstrated. Buffer sizes of less than 20 cells and loss rates larger than 10^{-4} are, however, untypical for ATM networks.

The same observations can be made from Figure 5, which shows curves for different multiplexer loads ρ_M if the buffer accommodates $S_M = 10$ cells. Despite a constant load ρ_M, both cell loss rate p_M and mean cell delay $\bar{d}_M$ increase with the number of sources N. Due to the statistical multiplexing gain, which grows with the number of sources, the effect becomes less distinctive when the number of traffic sources is large. The reduction of the tendency to underestimate the multiplexer performance objectives with the number of sources can clearly be observed in Figure 5(a).



(a) *Cell loss performance*

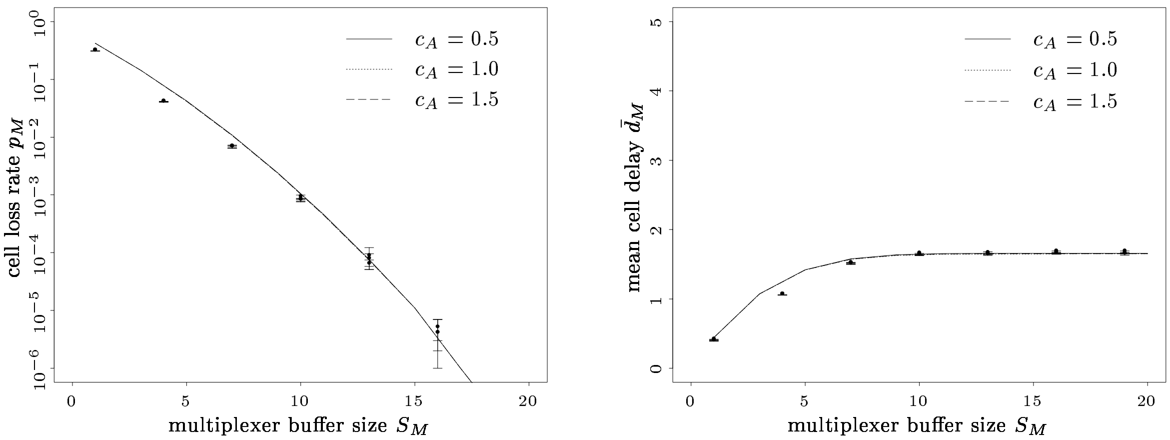
(b) *Delay performance*

Figure 5: *System performance for different multiplexer loads* ρ_M

The examples presented so far, and a large number of further parameter studies, lead to the following conclusion. Aiming at realistic traffic scenarios with a large number of connections, switch buffers having a size of a few hundreds of cells, and a network load less than 90%, the decomposition approach suggested in this paper provides reasonably accurate results at a low computational complexity. Therefore, after checking the accuracy and the basic system behavior, the effectiveness of traffic shaping at the UNI is investigated in the remainder of this section.

The first example demonstrates the smoothing effect of traffic shaping for cell arrivals following renewal processes with different coefficients of variation c_A. Each of the $N = 100$ traffic sources generates cells according to a negative-binomial distribution, resulting in a total multiplexer load $\rho_M = 0.8$. The shaper enforces a minimum inter-cell distance of $T = 100$ cells and its buffer is dimensioned to obtain a cell loss rate $p_S < 10^{-4}$.

Since the interface process is solely characterized by the traffic intensity of the spacer output process, the results derived by the decomposition approach are independent of the coefficient of variation c_A (cf. Figure 6). In the case of simulation, differences in performance are expected since the traffic load at the shaper is about $\rho_S = 0.8$. That is, bursts are not completely absorbed. Figure 6 shows, however, that performing traffic shaping at the UNI with a moderate shaper load ρ_S allows to obtain a multiplexer performance which is almost independent of the degree of variation of the renewal process. Of course, the mean delay introduced due to traffic shaping increases with the coefficient of variation.



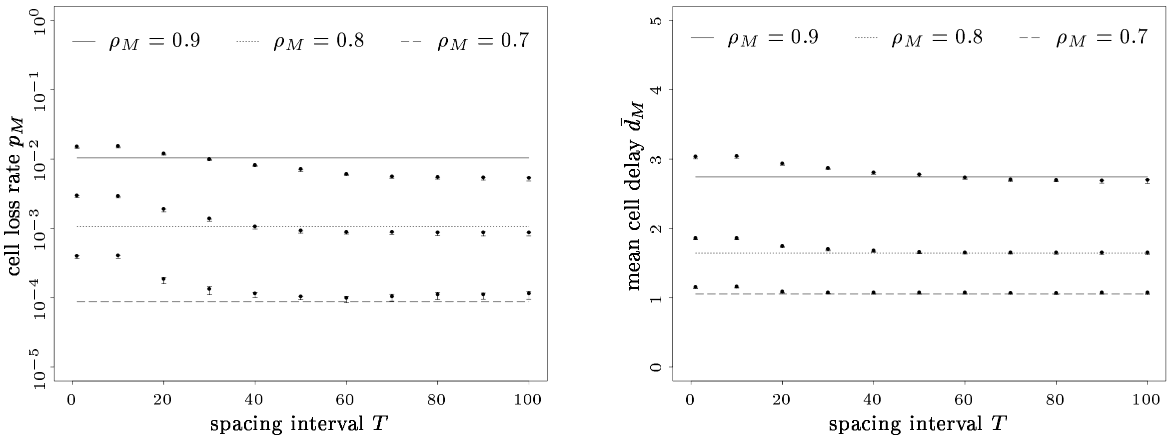
(a) *Cell loss performance*

(b) *Delay performance*

Figure 6: *Smoothing effect for arrivals following a renewal process*

Figure 7 shows the cell loss rate and the mean cell delay as a function of the spacing interval T to investigate the influence of the shaper load ρ_S on the effectiveness of traffic shaping at the network ingress. Again, $N = 100$ sources are considered, generating geometric arrivals according to the target multiplexer load ρ_M. The buffer at the shaper is dimensioned large enough to avoid cell loss and the buffer at the multiplexer accommodates $S_M = 10$ cells. For this configuration, the decomposition approach provides results which are independent of the spacing interval T, since no cells are lost at the shaper and the arrival rate of the traffic sources remains constant. Contrary, the simulation results are influenced by the length of the interval T, because bursts of cells can pass the shaper when T is small.

This effect can be observed for shaper loads lower than $\rho_S = 0.4$, that is $T < 50$ cells in the case of a multiplexer load of $\rho_M = 0.8$. The cell loss rate and the mean cell delay determined by simulation begin to increase for smaller loads, while the analytical results are not affected. No shaping corresponds to a spacing interval of $T = 1$ cell. Considering traffic sources modeled by renewal processes, the efficiency of traffic shaping thus increases until a shaper load of about $\rho_S = 0.4$ is achieved. Smoothing the traffic above this level does not result in a considerable growth of statistical multiplexing gain. For other traffic scenarios with the same relation between number of sources and multiplexer buffer size,



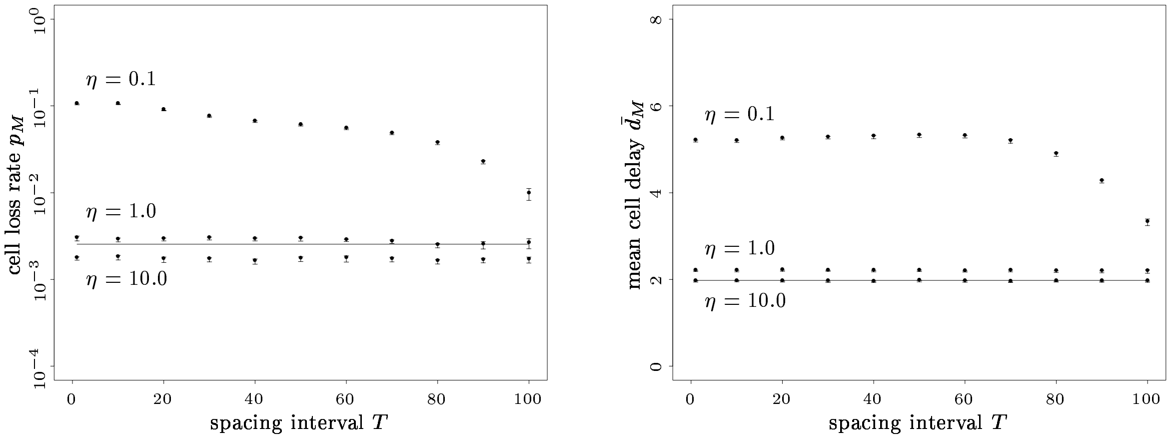
(a) *Cell loss performance*

(b) *Delay performance*

Figure 7: *Effectiveness of traffic shaping as a function of the spacing interval T*

similar observations can be made.

However, these findings do not match for cases with more bursty traffic, which is generated, for example, by on/off-sources. Figure 8 shows the same study using on/off-sources and a multiplexer load of $\rho_M = 0.8$. Different ratios η between mean length of on-states and mean length of off-states are considered. Both state lengths follow geometric processes and the load is kept constant by varying the deterministic cell arrival rate during on-states. If the mean length of on-states is ten times longer than that of off-states, that is $\eta = 10.0$, the traffic is very smooth and the performance of the multiplexer is accurately approximated by the decomposition approach, which provides results independent of the ratio η. Equal



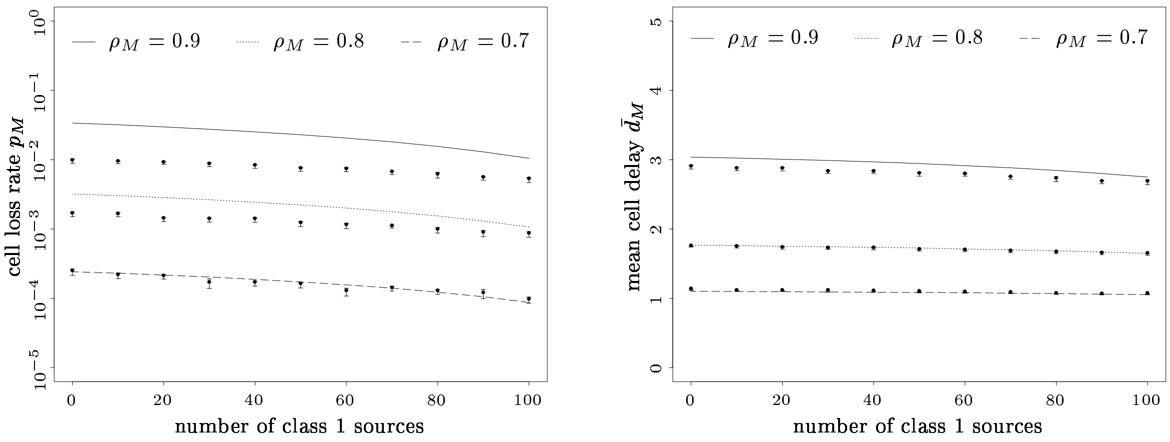
(a) *Cell loss performance*

(b) *Delay performance*

Figure 8: *Effectiveness of traffic shaping for on/off-sources*

mean lengths of on- and off-states, resulting in a more bursty traffic, increase the cell loss rate p_M and the mean cell delay $\bar{d}_M$ only slightly. If the off-states are, however, ten times longer in equilibrium than on-states, then the performance decreases considerably due to the burstiness of the arrival process. This effect is not considered by the analysis, since the interface process does not model correlation structures. The shaper has now to be loaded by more than $\rho_S = 0.8$, which corresponds to $T = 100$, to efficiently space cells with respect to the statistical multiplexing gain at the network ingress. For such high load ρ_S, the accuracy of the decomposition approach is reasonably high again.

In a last numerical example, the application of the decomposition approach to scenarios with heterogeneous traffic sources is investigated. Figure 9 shows the cell loss ratio p_M and the mean cell delay $\bar{d}_M$ for two classes of sources with geometric cell inter-arrival distributions, where the mean for class 2 sources is twice as large as that for class 1 sources. Furthermore, the spacing interval is set to $T = 100$ for class 1 sources and $T = 200$ for class 2 sources, and cell loss at the shapers is avoided by associating buffers which are sufficiently large. In Figure 9, simulation and analytical results are presented for three different multiplexer loads ρ_M and a buffer size of $S_M = 10$ cells. The load ρ_M is kept constant by substituting one class 1 source by two class 2 sources. Thus, zero on the x-axis represents a homogeneous scenario with 200 sources of class 2. To compute the analytical results, a homogeneous scenario with the same number of sources but periodic arrivals corresponding to the mean inter-arrival time of all sources was used. For all mixes of sources, a good agreement between simulation and analysis is observed. As for homogeneous scenarios, the simulation results for higher loads ρ_M are slightly overestimated due to approximating the finite buffer by the tail behavior of a infinite buffer model. Both Figures 9(a) and 9(b) reveal the decrease of system performance for larger numbers of sources.



(a) *Cell loss performance*

(b) *Delay performance*

Figure 9: *Approximation accuracy for heterogeneous sources*

5 Conclusions

In this paper, the effectiveness of traffic shaping at the user-network interface is investigated with respect to the statistical multiplexing gain at the network ingress. To consider realistic network scenarios with a large number of traffic sources, a decomposition approach for the performance analysis of a user-network interface model is presented. The approach, which is of a low numerical complexity, uses the mean cell inter-departure time from the shapers to characterize the interface process linking together the two model components.

The approximation accuracy of the decomposition approach increases with the number of sources, the load at the shaper, and the queue length at the multiplexer. High multiplexer loads influence the accuracy in a negative sense. From the discussion of the numerical results presented in this paper, a reasonable accuracy for realistic network scenarios is concluded.

The effectiveness of traffic shaping at the user-network interface can be assessed as follows. The more bursty the cell arrivals are, the higher the shaper must be loaded to obtain benefits from traffic shaping. Especially critical are on/off-sources, where a shaper load of more than 80 percent is required in order to increase network performance. This, however, may result in long shaping delays which can not be tolerated by every application on top. Effective traffic shaping at the user-network interface can therefore only be applied for non-real-time applications. Real-time connections should not be subjected to shaping.

Acknowledgments

The author would like to thank Frank Sierck for the stimulating discussions during the course of this work. Furthermore, the financial support of the Deutsche Telekom AG (Technologiezentrum Darmstadt) is appreciated.

References

[1] Z. Bazanowski, U. Killat, and J. Pitts. *The ND/nD/1-Model and its Application to the Spacing of ATM Cells.* Proceedings of the International Conference on Informational Networks and Systems '94, Saint-Petersburg, 1994, pp. 109-118.

[2] V. E. Beneš. *General Stochastic Processes in the Theory of Queues.* Addison Wesley, 1963.

[3] C. Blondia and O. Casals. *Traffic Profiles in ATM Networks.* Telecommunication Systems, Vol. 5, 1996, pp. 49-69.

[4] B. Boyer, F. M. Guillemin, M. J. Servel, and J. P. Coudreuse. *Spacing Cells Protects and Enhances Utilization of ATM Network Links.* IEEE Network, September 1992, pp. 38-49.

[5] I. Cidon, M. Sidi. *Performance Analysis of Asynchronous Transfer Mode (ATM) Systems.* IBM Technical Report RC 14395, Yorktown Heights, 1989.

[6] I. Cidon, R. Guerin, I. Kessler, and A. Khamisy. *Analysis of a Statistical Multiplexer with Generalized Periodic Sources.* Queueing Systems, Vol. 20, 1995, pp. 139-169.

[7] A. I. Elwalid and D. Mitra. *Analysis and Design of Rate-Based Congestion Control of High Speed Networks, I: Stochastic Fluid Models, Access Regulation.* Queueing Systems, Vol. 9, 1991, pp. 29-64.

[8] J. García, J. M. Barcelo, and O. Casals. *An Exact Model for the Multiplexing of Worst Case Traffic Sources.* Proceedings of the 6th International Conference on Data Communication Systems and Their Performance, Istanbul, 1995, pp. 480-491.

[9] H. Hemmer and P. T. Huth. *Evaluation of Policing Functions in ATM Networks.* Proceedings of the 13th ITC, Copenhagen, 1993, pp. 111-116.

[10] F. Hübner and P. Tran-Gia. *Performance of a Finite Capacity Asynchronous Multiplexer with Modulated Input.* Telecommunication Systems, Vol. 1, 1993, pp. 263-278.

[11] F. Hübner. *Discrete-Time Analysis of the Busy and Idle Period Distribution of a Finite-Capacity Multiplexer with Periodic Input.* Performance Evaluation, Vol. 21, 1994, pp. 23-36.

[12] F. Hübner and P. Tran-Gia. *Discrete-Time Analysis of Cell Spacing in ATM Systems.* Telecommunication Systems, Vol. 3, 1995, pp. 379-395.

[13] ITU Telecommunication Standardization Sector. *Recommendation I.413: B-ISDN User-Network Interface.* March 1993.

[14] ITU Telecommunication Standardization Sector. *Recommendation I.371: Traffic Control and Congestion Control in B-ISDN.* May 1996.

[15] K. Kvols and S. Blaabjerg. *Bounds and Approximations for the Periodic On/Off Queue with Applications to ATM Traffic Control.* IEEE INFOCOM '92, Florence, 1992, pp. 487-494.

[16] J. A. S. Monteiro, M. Gerla, and L. Fratta. *Input Rate Control for ATM Networks.* Proceedings of the 13th ITC, Copenhagen, 1993, pp. 117-122.

[17] I. Norros, J. W. Roberts, A. Simonian, and J. T. Virtamo. *The Superposition of Variable Bit Rate Sources in an ATM Multiplexer.* IEEE Journal on Selected Areas in Communications, Vol. 9, No. 3, 1991, pp. 378 387.

[18] J.-F. Ren, J. W. Mark, and J. W. Wong. *Performance Analysis of a Leaky-Bucket Controlled ATM Multiplexer*. Performance Evaluation, Vol. 19, 1994, pp. 73-101.

[19] M. Ritter. *Performance Analysis of Cell Rate Monitoring Mechanisms in ATM Systems*. Proceedings of the 3rd International Conference on Local and Metropolitan Communication Systems, Kyoto, 1993, pp. 129-150.

[20] M. Ritter. *Performance Analysis of the Dual Cell Spacer in ATM Systems*. 6th International Conference on High Performance Networking, Palma de Mallorca, 1995, pp. 345-362.

[21] J. W. Roberts and J. T. Virtamo. *The Superposition of Periodic Cell Arrival Streams in an ATM Multiplexer*. IEEE Transactions on Communications, Vol. 39, No. 2, 1991, pp. 298-303.

[22] The ATM Forum Technical Committee. *User-Network Interface Specification Version 3.1*. September 1994.

Preprint-Reihe
Institut für Informatik
Universität Würzburg

Verantwortlich: Die Vorstände des Institutes für Informatik.

[112] G. Buntrock, und G. Niemann. *Weak Growing Context-Sensitive Grammars.* Mai 1995.

[113] J. García and M. Ritter. *Determination of Traffic Parameters for VPs Carrying Delay-Sensitive Traffic.* Mai 1995.

[114] M. Ritter. *Steady-State Analysis of the Rate-Based Congestion Control Mechanism for ABR Services in ATM Networks.* Mai 1995.

[115] H. Graefe. *Konzepte für ein zuverlässiges Message-Passing-System auf der Basis von UDP.* Mai 1995.

[116] A. Schömig und H. Rau. *A Petri Net Approach for the Performance Analysis of Business Processes.* Mai 1995.

[117] K. Verbarg. *Approximate Center Points in Dense Point Sets.* Mai 1995.

[118] K. Tutschku. *Recurrent Multilayer Perceptrons for Identification and Control: The Road to Applications.* Juni 1995.

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