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Evaluation and comparison of cell loss and delay models for ATM multiplexers

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Abstract. Among several models that are available to represent the aggregate cell flow generated by on–off sources at an ATM multiplexer (either at an access or a switching node), the Interrupted Bernoulli Process (IBP) is characterized by particular simplicity and analytical tractability. The superposition of sources individually modeled as an IBP, whose cells enter a common buffer, is considered in this paper. The main goal is to compute approximations of two basic Quality of Service (QoS) indicators, namely, cell loss rate, whose analytical computation has been already presented in previous works, and the rate of cells exceeding a specified delay, whose presentation constitutes the theoretical novelty of the paper. Analytical expressions of these two quantities are given for homogeneous sources, i.e., possessing the same statistical parameters and QoS requirements. The analytical formulation is carefully evaluated by comparing the results obtained with others presented in the literature and with simulation results; in the latter, the actual cell arrival process is generated by means of a Markov Modulated Deterministic Process (MMDP) model of the on–off sources. Several comparisons are performed for different offered loads and by varying the buffer length, which show the effectiveness and the limits of the technique under investigation.

Key Words: ATM multiplexing, quality of service, performance evaluation

1. Introduction

In Asynchronous Transfer Mode (ATM) networks, the statistical multiplexing of cells associated to nonhomogeneous traffic flows (narrowband, broadband, time- or loss-sensitive, etc.) originates the need for a number of congestion control mechanisms that should be applied to meet the generally different performance requirements of the various users and ensure the necessary levels of Quality of Service (QoS). Moreover, the statistical description of many different sources involves a great effort in mathematical modelling, in order to capture the essential characteristics of the traffic.

In these respects, several source models have been proposed and analyzed, as well as bandwidth allocation and Call Admission Control (CAC) mechanisms (see, for instance, [13,14,17,19,20]). Concerning the latter, the acceptance of a new connection should be conditioned on the possibility of guaranteeing the required performance, with-out impairing that of the existing connections. Two main parameters that define the QoS of a connection are the cell loss probability (or the cell loss rate) and the probability (or rate) of cells whose delay exceeds a specified bound: their accurate estimation is very important, not only to evaluate the QoS, but also to carry out effective CAC schemes.

The issue of guaranteeing some specified delay limits (either at a single multiplexer or end-to-end) has been considered both with respect to deterministic and to stochastic [5,10] bounds. The latter may be sometimes preferable, due to a relative "elasticity" (see the discussion in [21, chapter 6] on this point).

The aim of this paper is to recall a scheme for the computation of cell loss rate and to test its accuracy, in a more homogeneous and complete form than in previous works [1,2] and to introduce and test an analytical formulation of the delayed cell rate in a multisource and multiservice class ATM multiplexer. The model of a source is based on the Interrupted Bernoulli Process (IBP), and it is used to derive the description of the superposition of multiple independent sources, in order to compute the cell loss rate and the delayed cell rate, by applying a "quasi-stationary" approximation (in a similar way as in [7]; see also discussions about similar situations in [21]). The model can be simply extended to include multiple source types that are grouped into service classes, served at the multiplexer according to the method of Service Separation (whereby a separate buffer and a portion of the link transmission capacity are dedicated to each class [18]). The approach in the present work is very similar to that presented in [22], where a very accurate analysis has been done with respect to the cell loss probability computation, by using Markov Modulated Deterministic Processes (MMDP) to describe the superposition of multiple homogeneous sources. Some of the numerical results reported at the end of this paper have been obtained under similar conditions and for the same traffic types as in [22], to give the opportunity to compare our results concerning cell loss rate with those reported therein.

The paper is organized as follows. In section 2 the IBP model is reviewed; in section 3 the computation of the lost and delayed cell rates is presented. In section 4 some numerical and simulation results show the accuracy and the limits of the model. Section 5 contains the conclusions.

2. Some models for bursty sources

As shown, for instance, in [6], an accurate description for several types of bursty sources can be given by a Talkspurt-Silence model, a two-state Markov chain alternating periods of activity (burst periods) and periods of silence. A specific case where this model is particularly in accordance with reality is that of voice sources [4]. In the case of data, it must be applied with some attention because this model does not always approximate with accuracy the data traffic, as the results on the nature of LAN and also wide area TCP/IP data traffic have demonstrated [12,15,16]. Within a burst period, cells are generated with known and constant bit-rate. If the model is considered in the continuous-time domain, the sojourn times in both states are exponentially distributed with known mean value. If it is used in the discrete-time domain, sojourn times have

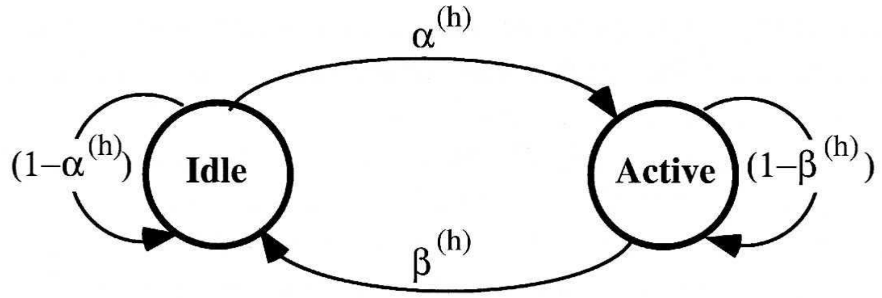

Figure 1. IBP bursty source model.

geometric distribution and the model is equivalent to a two-state MMDP with one silence state [6]; as already said, this approach and its use in the computation of the cell loss probability in ATM multiplexers have been extensively analyzed in [22].

Considering a channel with capacity C bits/s, a bursty connection of a particular traffic class h can be described by a two-state model: "active" and "idle", as in the Talkspurt–Silence discrete-time model.

We consider a traffic class h composed by homogeneous sources with the same statistical parameters, i.e., peak bandwidth $P^{(h)}$ bits/s, average bandwidth $W^{(h)}$ bits/s, mean value of the burst length (in cells) $B^{(h)}$ and value of the burstiness $b^{(h)} = P^{(h)}/W^{(h)}$. The probabilities to be in the "idle" and "active" state, respectively, are:

$$\omega_{\mathrm{i}}^{(h)} = \frac{\beta^{(h)}}{\alpha^{(h)} + \beta^{(h)}} = \frac{b^{(h)} - 1}{b^{(h)}}, \tag{1}$$

$$\omega_{\mathrm{a}}^{(h)} = \frac{\alpha^{(h)}}{\alpha^{(h)} + \beta^{(h)}} = \frac{1}{b^{(h)}}, \tag{2}$$

where

$$\alpha^{(h)} = \frac{1}{B^{(h)}(b^{(h)} - 1)} \quad \text{and} \quad \beta^{(h)} = \frac{1}{B^{(h)}}.$$

It is important to note that (1) and (2) are independent of the burst length.

Within the active state, the arrival process of cells is modelled by a Bernoulli process: at each time instant, there is a cell arrival with probability $\Gamma^{(h)} = 1/M^{(h)}$ with $M^{(h)} = C/P^{(h)}$.

3. Cell loss rate and delayed cell rate computation

We consider $N^{(h)}$ connections of class h multiplexed in a buffer of size Q (cells), served by a single link with capacity C bits/s. Each connection is supposed to be described by the IBP bursty source model introduced in section 2, and each source is considered to be independent of the others. If the number of connections in the active state at any given instant is n, the probability $f_j^{(h)}(n)$ of having j connections of traffic class h generating a cell with n connections of the same class in the active state is

$$f_j^{(h)}(n) = \binom{n}{j} \left(\Gamma^{(h)}\right)^j \left(1 - \Gamma^{(h)}\right)^{n-j}, \quad 0 \leqslant j \leqslant n, \tag{3}$$

and its average value is given by

$$\sum_{j=0}^{n} j \cdot f_j^{(h)}(n) = n\Gamma^{(h)}. \tag{4}$$

By conditioning to the number n of active connections, the steady-state value of the "instantaneous" cell loss rate (see also [11]) can be computed as

$$p_{\text{loss}}^{(h)}(n, Q) = \sum_{i=0}^{Q-1} \frac{\sum_{j=0}^{n} \max(i + j - Q, 0) f_j^{(h)}(n)}{n\Gamma^{(h)}} \pi_i^{(h)}. \tag{5}$$

The numerator in (5) represents the average number of lost cells in a slot, given i cells inside the buffer, while the denominator is the average number of arrived cells. The ratio of these two quantities represents the rate of lost cells during a slot time, given a fixed buffer dimension. Actually, it is a ratio of averages (or a rate) and it will approximate the probability that an arriving cell during a time slot finds the buffer full given the number n of connections in the active state. This ratio is averaged over the quantities $\pi_i^{(h)}$, which represent the steady state probabilities of having i cells inside the buffer, given n active connections. The values of $\pi_i^{(h)}$ are computed by using the transition matrix $A^{(h)}$, whose elements $a_{ij}^{(h)}(n, Q)$ represent the probability of transition from the state where i cells are queued in the kth slot to the state where j cells are queued in the $(k + 1)$th slot, given n active connections. The calculation of $a_{ij}^{(h)}(n, Q)$ is done by using the AF (Arrivals First) policy to model the process of simultaneous arrivals in and departures from the queue ([8]; see also [19, appendix]). Figure 2 shows the behavior of the policy over time in more detail. Time is divided into slots, whose length is $T_s = L/C$ s, where C [bits/s] is the channel capacity and L bits is the length of a cell (424 bits). "Ar" identifies the arrival process of cells; "Sv" stands for Service and

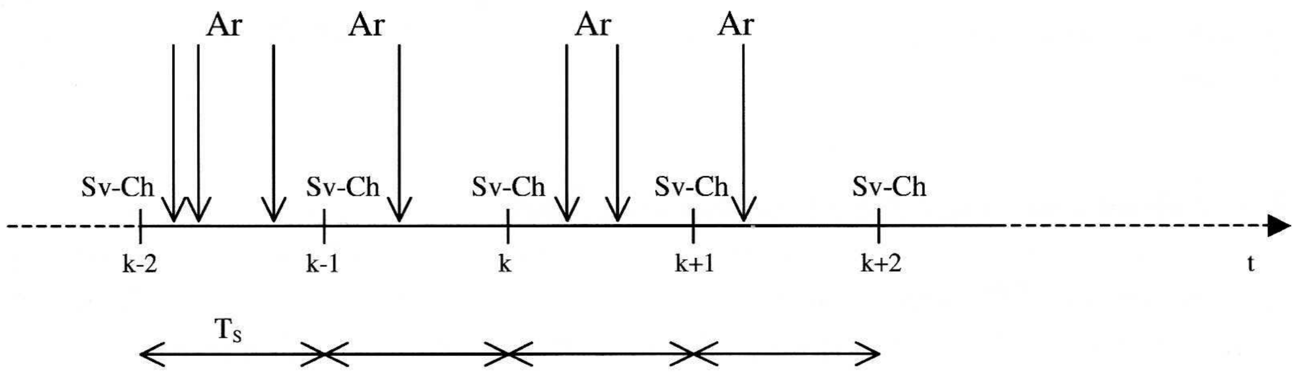

Figure 2. Behavior of the arrival and of the service policy.

represents the service instant; "Ch" stands for "status Check", and it is the time when the status of the queue is verified. All the arrivals (Ar) are distributed along a cell duration. There is no time distinction between service time (Sv) and queue status check (Ch), so that the events Sv and Ch happen at each generic discrete time instant k; the difference is that the system status is verified after the service, i.e., after the first queued cell, if present, has been transferred to the server; the transfer time from the queue to the server is considered negligible.

Thus, we obtain:

$$a_{ij}^{(h)}(n, Q) = \begin{cases} 0, & j < i - 1, \\ f_{j-i+1}^{(h)}(n), & i - 1 \leqslant j < Q - 1, \\ \sum_{s=Q-i}^{n} f_s^{(h)}(n), & j = Q - 1, \end{cases} \tag{6}$$

$$a_{0j}^{(h)}(n, Q) = \begin{cases} f_0^{(h)}(n) + f_1^{(h)}(n), & j = 0, \\ f_{j+1}^{(h)}(n), & 0 < j < Q - 1, \\ \sum_{s=Q}^{n} f_s^{(h)}(n), & j = Q - 1. \end{cases} \tag{7}$$

The steady state probability distribution

$$\Pi^{(h)} = \left[\pi_0^{(h)}, \pi_1^{(h)}, \ldots, \pi_{Q-1}^{(h)}\right] \tag{8}$$

for the queue length can be obtained by solving the following set of linear equations:

$$\Pi^{(h)} = \Pi^{(h)} A^{(h)}, \tag{9}$$

$$\sum_{i=0}^{Q-1} \pi_i^{(h)} = 1 \tag{10}$$

(note that, owing to the fact that transitions occur just after the beginning of service, the state $i = Q$ can never be reached; actually, the server can be considered outside the queue in the AF model: see also [19, appendix]).

Our aim, however, is to compute the average cell loss rate $P_{\text{loss}}^{(h)}(N^{(h)}, Q)$ in the multiplexer. By letting

$$v_n^{N^{(h)}} = \binom{N^{(h)}}{n} \left(\omega_{\text{a}}^{(h)}\right)^n \left(\omega_{\text{i}}^{(h)}\right)^{N^{(h)}-n} \tag{11}$$

be the steady state probability of having only n active connections out of $N^{(h)}$ connections in the system, the average cell loss rate can be approximated (see the discussion at the end of this section) as

$$P_{\text{loss}}^{(h)}\left(N^{(h)}, Q\right) = \sum_{n=0}^{N^{(h)}} p_{\text{loss}}^{(h)}(n, Q) \cdot v_n^{N^{(h)}}. \tag{12}$$

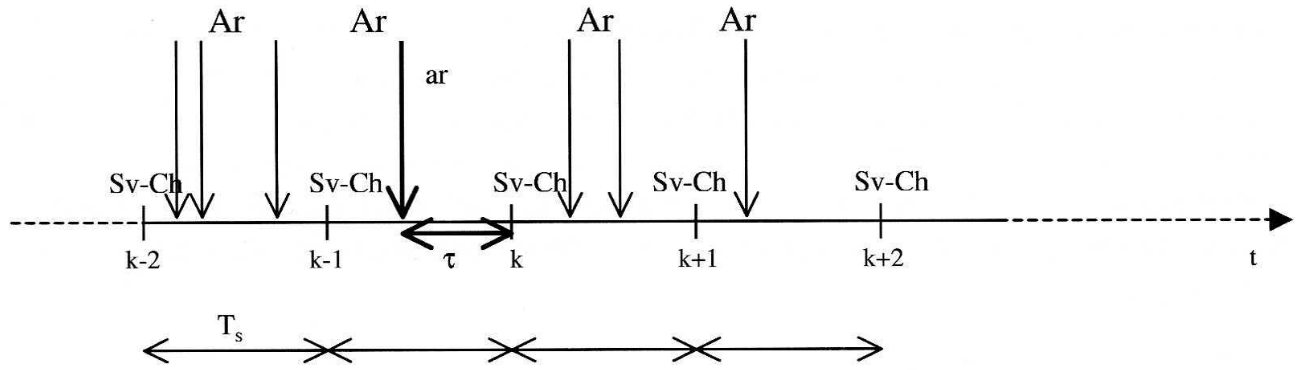

Figure 3. Arrival "a" of a generic cell.

The following procedure can be used to compute the rate of cells delayed longer than $D^{(h)}$ s for class h, (delayed cell rate). The first step is computing the permanence time $T_{\rm p}^{(h)}(N_{\rm c}^{(h)})$ of a cell in the overall system (defined as the queue and the server), if $(N_{\rm c}^{(h)})$ cells are currently queued when the cell under analysis arrives.

If the notation and the arrival sequence introduced in figure 2 are recalled (figure 3), the arrival of the cell under study is identified with "ar", and $\tau (0 \leqslant \tau \leqslant T_S = L/C)$ is defined as the time elapsing from the arrival instant to the first Sv (and Ch) time, then $T_{\rm p}^{(h)}(N_{\rm c}^{(h)})$ may be computed as

$$T_{\rm p}^{(h)}\left(N_{\rm c}^{(h)}\right) = N_{\rm c}^{(h)}\frac{L}{C} + \frac{L}{C} + \tau, \tag{13}$$

where L/C is the service time of the cell.

An arriving cell is considered delayed if it suffers a delay longer than $D^{(h)}$, equation (14) shows the corresponding delay constraint

$$T_{\rm p}^{(h)}\left(N_{\rm c}^{(h)}\right) \leqslant D^{(h)}. \tag{14}$$

In more detail,

$$N_{\rm c}^{(h)}\frac{L}{C} + \frac{L}{C} + \tau \leqslant D^{(h)} \Rightarrow N_{\rm c}^{(h)} \leqslant \left\lfloor D^{(h)}\frac{C}{L} - 1 - \tau\frac{C}{L}\right\rfloor, \tag{15}$$

where $\lfloor x \rfloor$ represents the largest integer less than or equal to x.

Let $L_Q^{(h)}$ be the offset from the head of the buffer, in cells, beyond which a cell suffers a delay longer than $D^{(h)}$: for the computation in (15),

$$L_Q^{(h)} = \left\lfloor D^{(h)}\frac{C}{L} - 1 - \tau\frac{C}{L}\right\rfloor. \tag{16}$$

The value τ, measured in the simulations, must be fixed to obtain a model. There are various possibilities; the authors have chosen to compare the behavior in the two "extreme" values: $\tau = 0$ and $\tau = T_S = L/C$. In the first case, called Non-Conservative (NC), in the following

$$L_Q^{(h)} = \left\lfloor D^{(h)}\frac{C}{L} - 1\right\rfloor, \tag{17}$$

while, in the second case, called Conservative (C), in the following

$$L_Q^{(h)} = \left\lfloor D^{(h)} \frac{C}{L} - 2 \right\rfloor. \tag{18}$$

By conditioning again to a fixed number n of active connections, the steady-state value of the "instantaneous" delayed cell rate can be computed as

$$p_{\text{delay}}^{(h)}(n, Q) = \sum_{i=0}^{L_Q^{(h)}} \frac{\sum_{j=0}^{n} \min[\max(i + j - L_Q^{(h)}, 0), \max(Q - L_Q^{(h)}, 0)] f_j^{(h)}(n)}{n\Gamma^{(h)}} \pi_i^{(h)}$$
$$+ \sum_{i=L_Q^{(h)}}^{Q-1} \frac{\sum_{j=0}^{n} \min[\max(j, 0), \max(Q - L_Q^{(h)}, 0)] f_j^{(h)}(n)}{n\Gamma^{(h)}} \pi_i^{(h)}. \tag{19}$$

By using the same quantities considered above for the cell loss rate, the average delayed cell rate can be approximated as

$$P_{\text{delay}}^{(h)}\left(N^{(h)}, Q\right) = \sum_{n=0}^{N^{(h)}} p_{\text{delay}}^{(h)}(n, Q) \cdot v_n^{N^{(h)}}. \tag{20}$$

The use of the stationary distributions, $\pi_i^{(h)}$, $i = 0, 1, \ldots, Q - 1$ and $v_n^{N^{(h)}}$, $n = 0, \ldots, N^{(h)}$, instead of the joint stationary distribution of the number of cells in the buffer and the number of active calls, is suggested by the large difference in the time scales between the cell and the active connections dynamics. In more detail, due to the previous assumption, the steady state values (5) and (19) can be supposed to be approximations of the real cell loss rate and of the delayed cell rate, respectively, between two consecutive instants where the number n of active connections changes. Our aim in this paper is to evaluate the approximation of the cell loss rate and delayed cell rate, as given by (12) and (20), on some specific examples by simulation.

The results obtained for a single traffic class in the previous section can be easily extended to a multiple class situation if service separation is supposed to be used, with a complete partitioning control policy [3,18] to manage the admission of the calls of the different classes. From the point of view of the multiplexer, this means that a different buffer of length $Q^{(h)}$ is assigned to each traffic class $h = 1, \ldots, H$, with H the number of classes, and a scheduler serves each buffer according to a portion $V^{(h)}$, which we call "virtual capacity", of the total capacity C of the outgoing link. Under complete partitioning, we must have that

$$\sum_{i=1}^{H} V^{(h)} = C. \tag{21}$$

In this case, each traffic class h "sees" a virtual multiplex with buffer length $Q^{(h)}$ and channel capacity $V^{(h)}$. So, for each class h, the same formulas as before can be used, with $V^{(h)}$ and $Q^{(h)}$ substituting C and Q, respectively.

4. Numerical results

In this section the cell loss rate and delayed cell rate approximations that were introduced previously are computed for some specific traffic classes and compared with some other methods reported in the literature and with simulation results obtained by using a tool specifically designed for the aim. Three different traffic classes (the same as in [22]), whose parameters are reported in table 1, have been used in the simulations. The criterion used to stop the simulations is that the width of the 95% confidence interval be less then 3% of the estimated value of the cell loss and delayed cell rate.

All the quantities that have been evaluated are compared with the simulation results obtained by using an independent Talkspurt-Silence source traffic generator for each connection in the system. The quantities of interest are plotted versus the buffer length with fixed numbers of sources. As regards the cell loss rate, besides the computation based on the IBP as introduced above (namely, equations (12) and (20), generally referred to in following as "IBP model"), three other methods have been considered for comparison. Two of them are taken from [22], and are indicated as $(M^{(h)}+1)$-state MMDP and 2-state MMDP, respectively. The former is rather accurate but computationally complex, whereas the latter is extremely simple, but can become highly imprecise (a 2-state model is used to represent the *aggregation* of the sources). The third method is based on the calculations used in [9] to derive a notion of equivalent bandwidth, and is termed "exponential approximation", due to the fact that each of the two models considered therein gives rise to an exponential form of the loss rate (see also [21, chapter 4]).

The first three graphs are aimed at showing the cell loss rate for three traffic classes ($h = 1, 2, 3$) matching real sources, like voice, fast data and image transmission, whose behaviour is well described by the Talkspurt-Silence model. The three classes share a single channel, where the total bandwidth ($C = 387$ Mbits/s) is divided into three partitions of 7, 350 and 30 Mbits/s, respectively. Figure 4 shows the behaviour of the voice sources, with 250 connections in progress. The IBP model is seen to be always conservative and to follow the shape of the simulative curve, though with a certain error that tends to amplify for larger buffers. The tendency of the IBP to follow the simulation curve, which will be confirmed also in other results below, indicates a certain capability to capture (to some extent) both cell-scale and burst-scale behaviour [17]. A similar be-

Table 1
Characteristics of the traffic classes.

h Traffic class	$P^{(h)}$ [Mbits/s]	$W^{(h)}$ [Mbits/s]	$B^{(h)}$ [cells]	$D^{(h)}$ [ms]
1 (voice)	0.064	0.022	58	1
2 (data)	10	1	339	0.1
3 (image)	2	0.087	2604	0.028

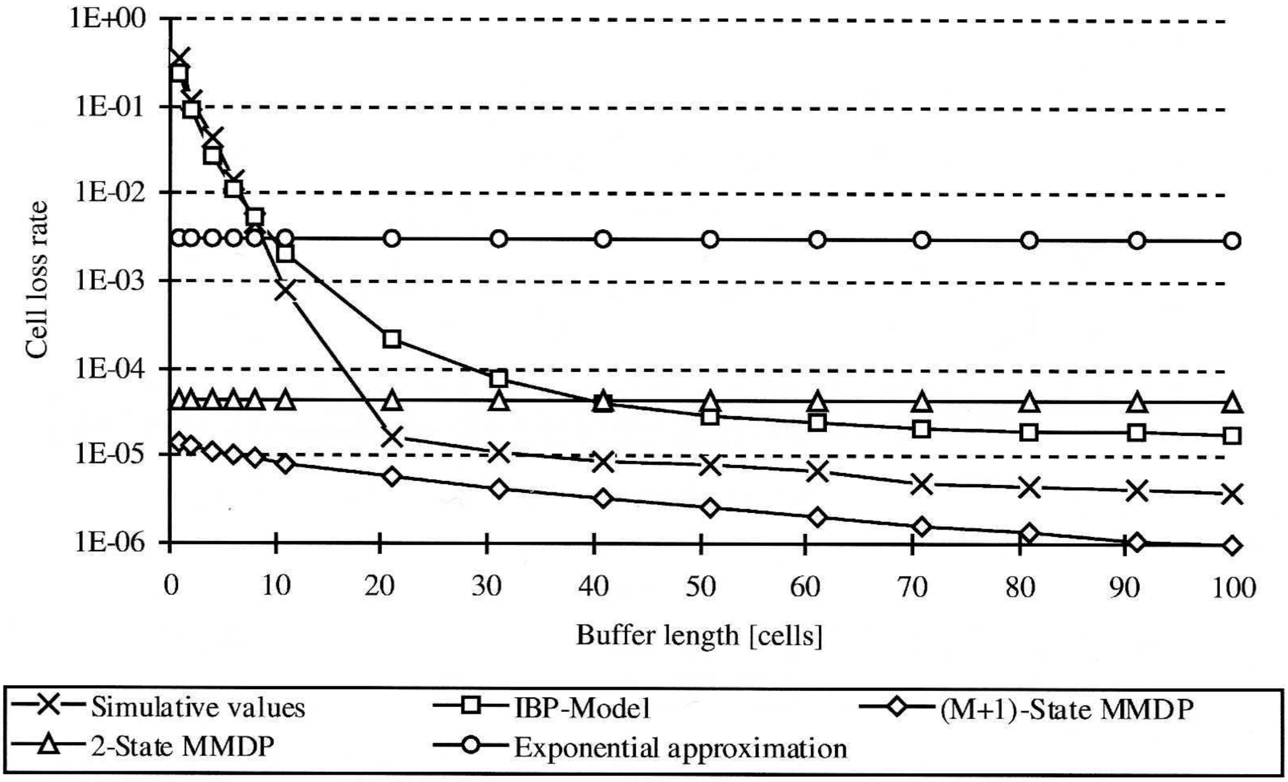

Figure 4. Cell loss rate versus buffer length, $h = 1$ (voice), $C^{(1)} = 7$ Mbits/s, and $N^{(1)} = 250$.

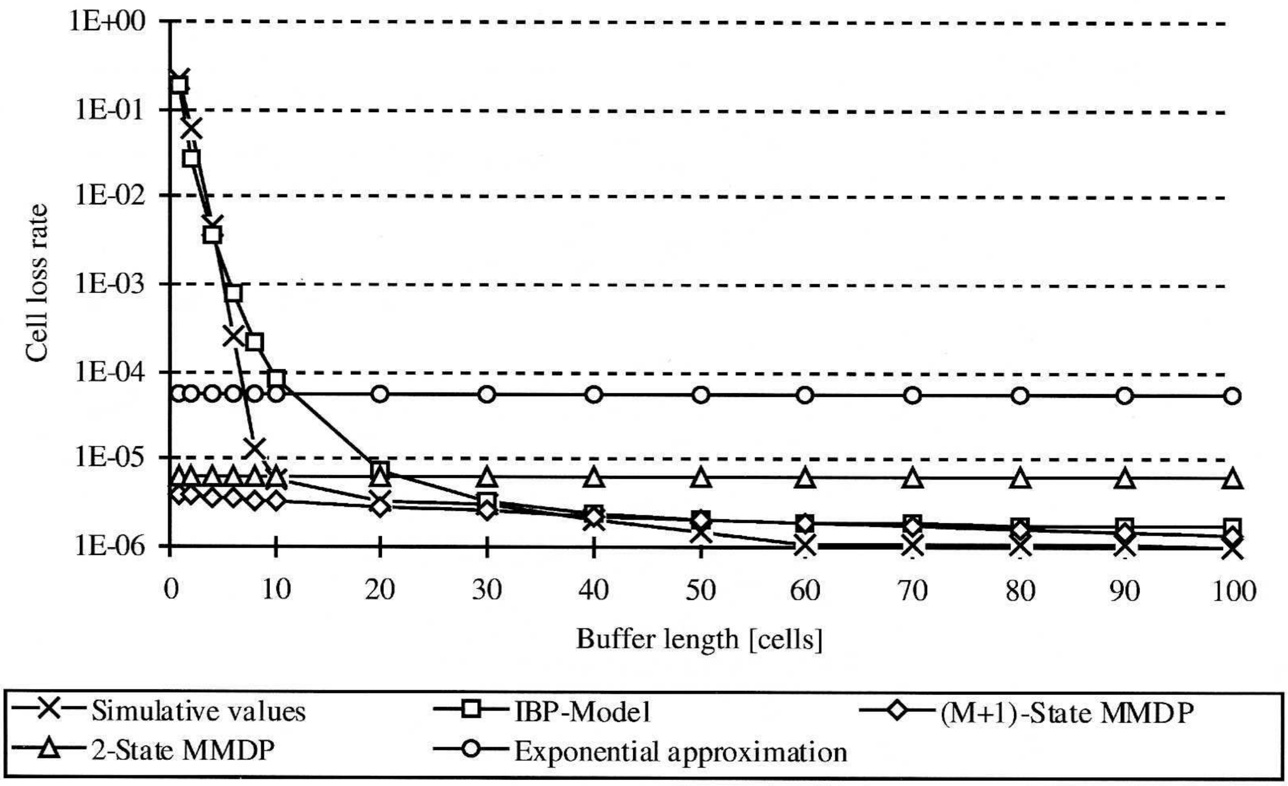

Figure 5. Cell loss rate versus buffer length, $h = 2$ (data), $C^{(2)} = 350$ Mbits/s and $N^{(2)} = 180$.

haviour can be observed for the data (figure 5) and the image (figure 6) sources (actually, both classes yield an even better approximation).

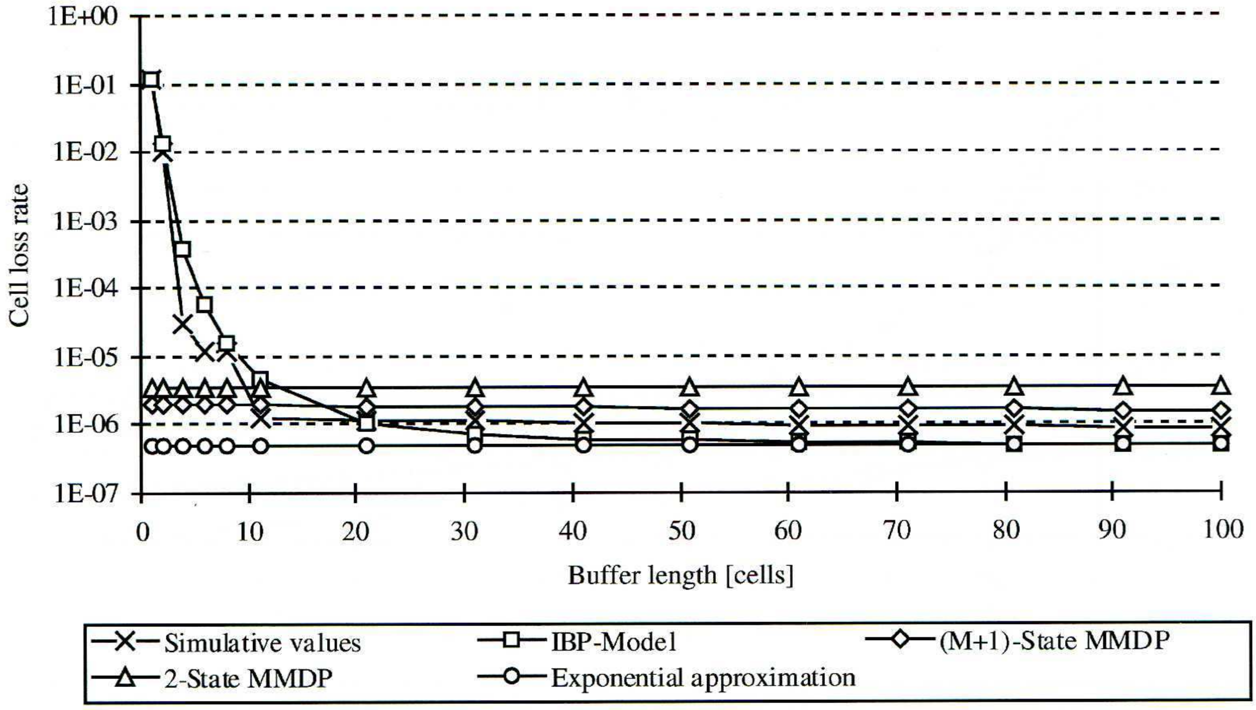

Figure 6. Cell loss rate versus buffer length, $h = 3$ (image), $C^{(3)} = 30$ Mbits/s, and $N^{(3)} = 100$.

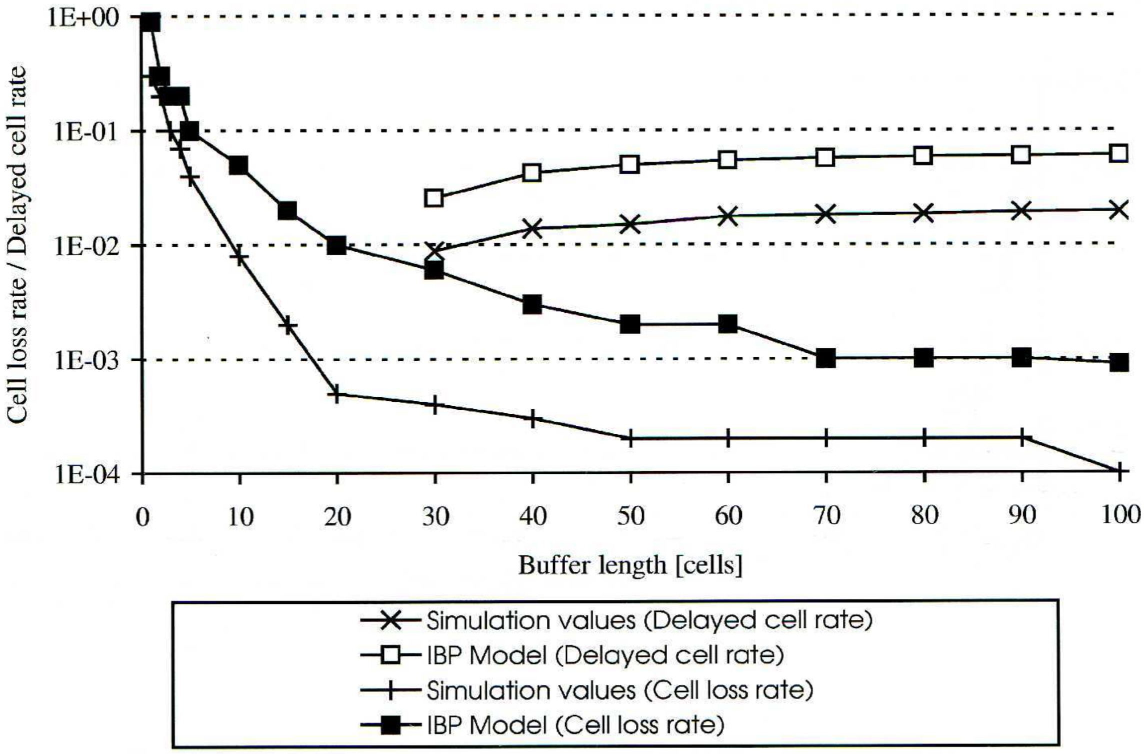

Figure 7. Delayed cell rate and cell loss rate versus the buffer length, $h = 1$ (voice), $C = 10$ Mbits/s, and $N^{(1)} = 400$.

Figures 7–9 show the behaviour of the IBP model approximation of the delayed cell rate, compared with simulative results; the cell loss rate is also reported on the same plot. All the graphs of the delayed cell rate have been calculated in the non-conservative case.

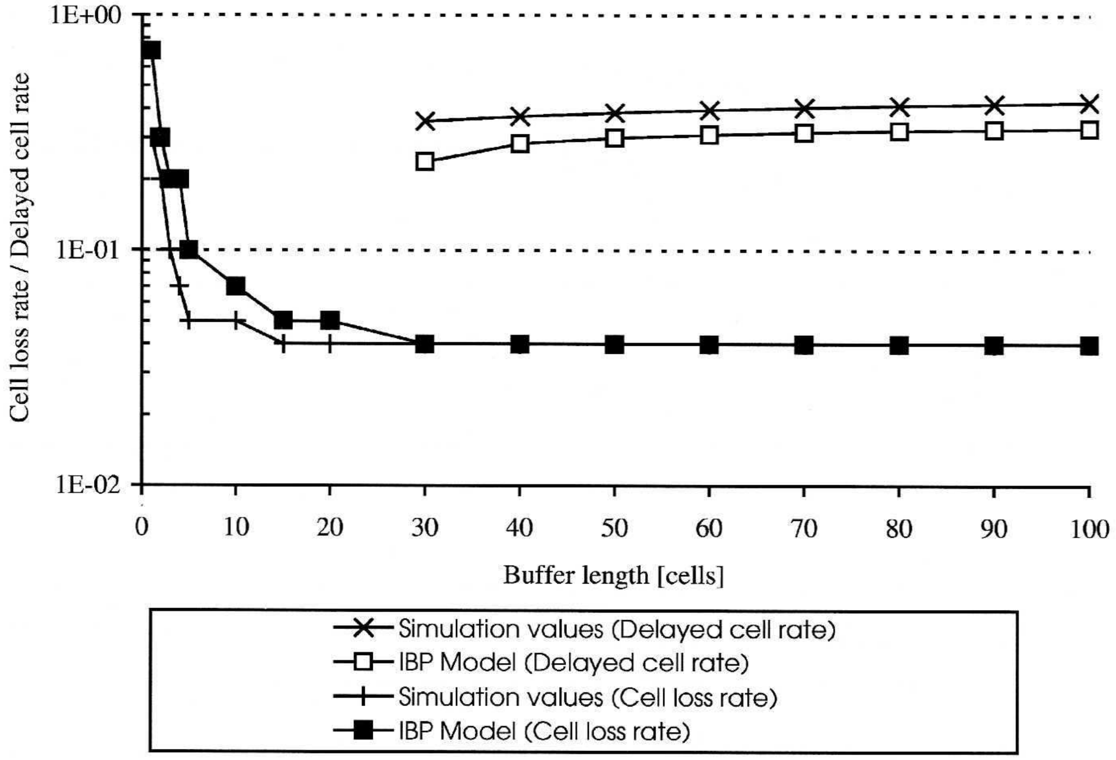

Figure 8. Delayed cell rate and cell loss rate versus the buffer length, $h = 2$ (data), $C = 100$ Mbits/s, and $N^{(2)} = 90$.

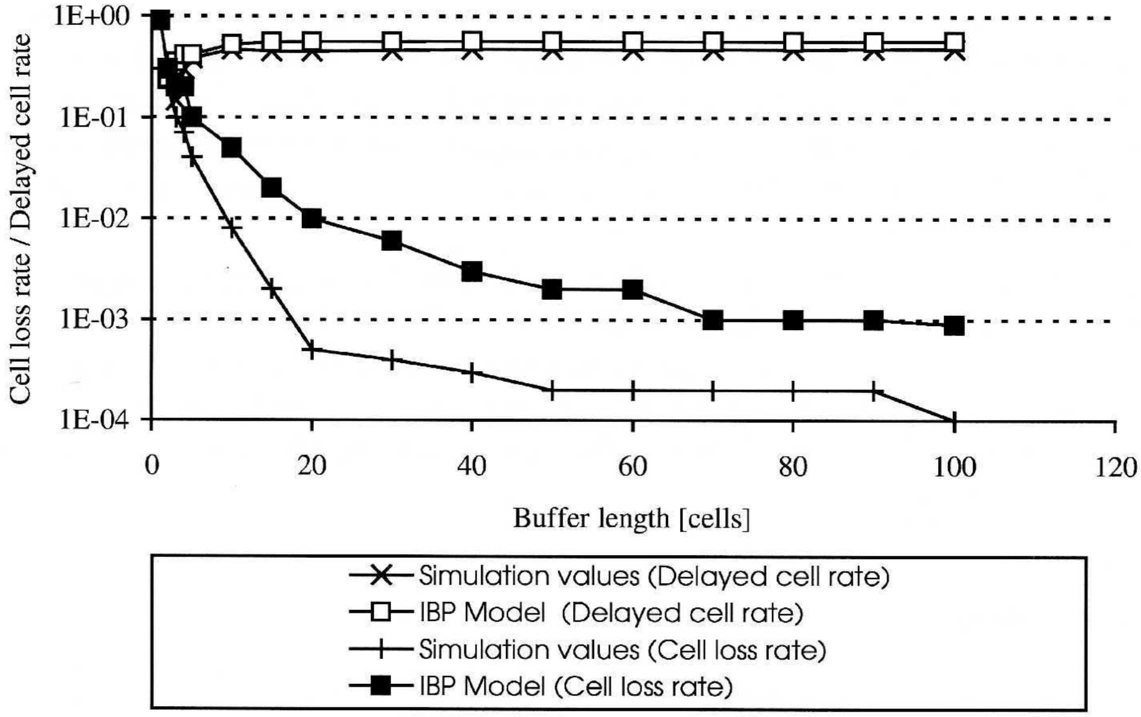

Figure 9. Delayed cell rate and cell loss rate versus the buffer length, $h = 3$ (image), $C = 40$ Mbits/s, and $N^{(3)} = 400$.

In particular, the first three classes ($h = 1, 2, 3$) have been considered and, in this test, they share a 150 Mbits/s output channel (10 Mbits/s to class 1, 100 Mbits/s to class 2 and 40 Mbits/s to class 3). The three graphs, one for each class, present substantially

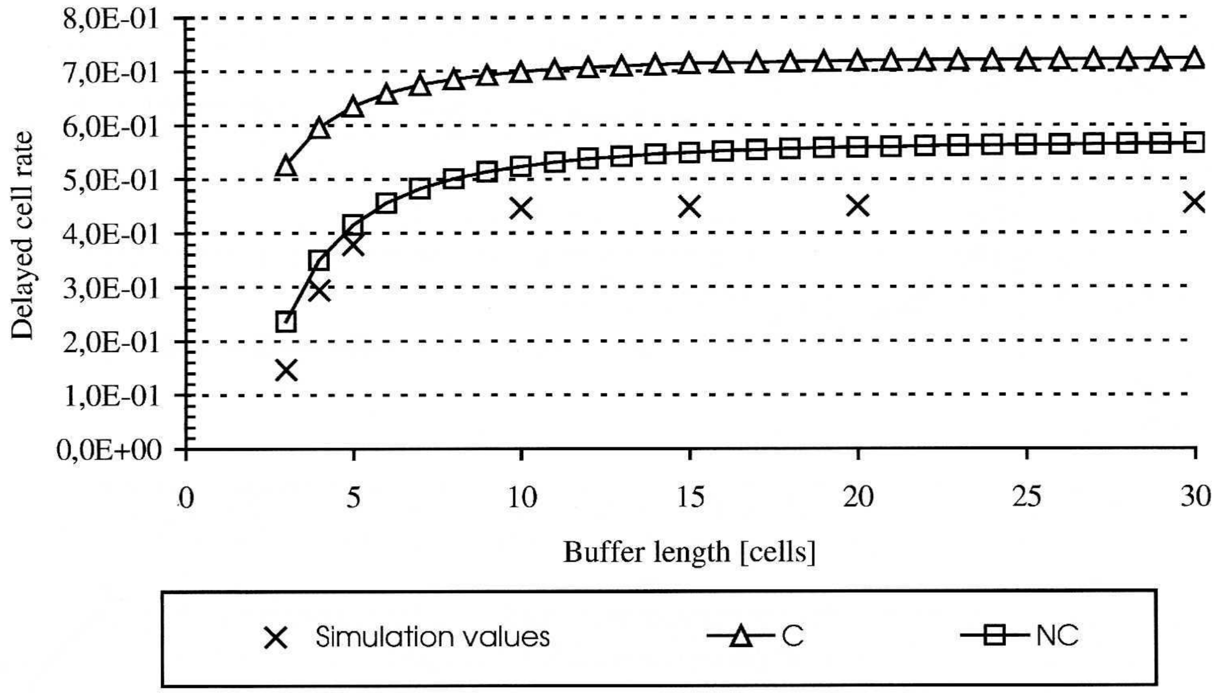

Figure 10. Delayed cell rate versus the buffer length, $h = 3$ (image), $C = 40$ Mbits/s, and $N^{(3)} = 400$.

the same situation, namely, a cell loss rate that reaches a more or less constant value beyond a certain buffer length. The delayed cell rate is null up to the threshold value $L_Q^{(h)}$ (the null values are not shown in the figures) but attains very large values in the range of buffer lengths that are more convenient for the cell loss rate. It can be noted that, in these cases, the cell loss rate analytical values are always conservative, in the sense that they are above the simulative ones whereas the same does not always happen for the delayed cell rate. The latter tends, anyway, to be rather independent of the buffer length.

Just to give an idea of the variation introduced by considering the two models called Conservative (C) and Non-Conservative (NC), we show, in figure 10, the two cases relatively to the same traffic class and capacity used in figure 9. The conservative model tends to overestimate the delayed cell rate. On the contrary, the NC case should underestimate the same quantity; but, in the case shown, the NC model provides a good approximation of the rate.

5. Conclusions

A model for the representation of the aggregation of bursty (on–off) traffic sources has been presented, and its effectiveness in computing the cell loss rate and delayed cell rate at an ATM multiplexer has been investigated. The case of one traffic class, where the multiplexer is loaded with a mix of multiple, statistically independent, homogeneous sources has been treated; but the model may be simply applied to the case of multiple source classes (characterized by different statistical features and/or performance requirements) assuming service separation with complete bandwidth partitioning. Two approximations have been derived of the desired quantities, stemming from the IBP model used to represent the behaviour of each source.

The accuracy of the approximations has been compared with simulation results and with other techniques presented in the literature, by using some test classes of traffic. The results suggest that the approximations proposed may be often regarded as a lower bound for performance analysis; when that is not true, the analytical values are, anyway, quite close to the values obtained by simulation.

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