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# Priority Management in ATM Switching Nodes

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**Abstract**—The future broadband ISDN needs a high degree of flexibility in order to cope with a great variety of services with widely differing bandwidth and quality of service requirements. The asynchronous transfer mode (ATM), which is now widely accepted as the basis for this network [2], offers very flexible information transfer with respect to bandwidth requirements. The introduction of a special class of priorities, called space priorities, adds a quality of service flexibility to the ATM bearer service. This paper describes various space priority mechanisms and their detailed performance evaluation. Furthermore, a comparative performance study is given, indicating the excellent performance characteristics of a simple buffer management scheme called partial buffer sharing.

## I. INTRODUCTION

THE load carried by a network is always the result of a trade-off between the demands of the network operator, with respect to transmission efficiency, and those of subscribers concerned with the quality of service, i.e., the *user-oriented quality of service* (QOS).

To achieve this user-oriented quality of service, end-to-end protocols include a user-specific ATM adaptation layer—above the network layer—which copes with the *network performance of the connection* and recovers transmission errors, cell losses, clock perturbation, and cell delay variations. Signal recovery can be properly worked out by the ATM adaptation layer only if the network performance is better than a set of lower bounds, namely the *network-oriented quality of service*.

Since the current ATM-based network offers a unique bearer service to indistinguishable cells, congestion control mechanisms have to ensure that the network performance of an ATM connection is higher than the network-oriented quality of service required by the most demanding service.

As far as cell loss is concerned, such a requirement may be very restrictive. Some applications, for example, signaling and subband coded video, involve *vital cells* which must be received by the adaptation layer.

Conversely, such a high-quality transfer is not required by all applications. Voice and data communications, which represent the majority of calls, could cope with higher cell loss rates and a larger cell delay jitter. Why should these subscribers pay for the best transfer quality?

Indeed, a congestion control designed for a current ATM-based network is likely to limit the multiplex load. This limitation may be rather severe when the network has to cope with bursty sources, even if an intelligent access mode is used. Net-

work operators are likely to require further load improvements, which cannot be delivered without increasing the cell loss rate and the cell delay variations.

Besides the current bearer service offering a *high-quality transfer*, a second bearer service could be defined offering a *medium-quality transfer*, which would provide for connections with less stringent network performance requirements. Among the different performance criteria, we have focused on *cell loss rate* since many services can tolerate a rather high cell loss rate.

Introducing a second bearer service would allow ATM networks to meet the requirements of a “quasi-zero” cell loss transfer while achieving a fairly high multiplex utilization. Moreover, it would improve the robustness of queue dimensioning when the network copes with unexpected bursty traffic.

An explicit cell loss priority indication in the ATM cell header has been recently agreed upon by CCITT [3].

## II. ATM BEARER CAPABILITIES AND PRIORITIES

The two bearer capabilities could be offered either at call level or at cell level. When offered at call level, all cells of a given call belong to the same class. Some data transfer calls could be based only on the *medium-quality transfer* bearer capability. When offered at cell level, each cell of a given call may be either *vital* or *ordinary*. Here, the basic idea is to take advantage of the intrinsic redundancy of the signals with respect to the adaptation layer. A *vital* cell must reach its destination if the adaptation layer is to retrieve the original signal. On the contrary, the loss of an *ordinary* cell does not matter since its payload can be retrieved by the adaptation layer. When the ratio of vital to ordinary cells is small, the requirement on cell loss becomes less severe so that the admissible load may be improved. Indeed, the unique cell loss rate requirement is now split into two parts: a more restrictive constraint on the loss of precious and infrequent cells and a less restrictive constraint on the loss of ordinary and frequent cells. However, this is paid for by priority marking in the terminals and a more complex buffer management logic in the switches and multiplexers.

Another possible application is the marking of cells by the policing function [8]. Cells which are violating the contract on which the admission of the corresponding connection is based will be marked as low priority cells. However, at most one of the above applications can be supported with only two priority classes.

The two bearer capabilities could be offered either separately or jointly on the network multiplexes. When offered separately, each bearer capability is assigned to a set of dedicated multiplexes. This is called the *Route Separation*, where *medium-quality transfer* multiplexes will carry a higher load than others. In this solution, call setup is complex but buffer management in the switching and multiplexing stages remains simple. For some calls involving both bearer capabilities, for example, video communication, a resequencing device must be added to the ATM adaptation layer because the ordering of cells can be mod-

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ified by their transfer along different virtual circuits through the network.

When offered jointly on any multiplex, two classes of cells, corresponding to different cell loss rates, should be defined. *Vital cells* are handled by the *high-quality transfer* bearer capability while *ordinary cells* are handled by the *medium-quality transfer* bearer capability. Buffer management in the switching elements becomes more complex since a selective discarding mechanism must be implemented.

Note that the introduction of the usual *head of the line* priority is *not* an appropriate solution. If this mechanism is implemented, both classes experience different sojourn time characteristics but *identical cell loss rates* since the time priority HOL is not a selective discarding mechanism.

We propose two priority mechanisms in the following, which both realize selective discarding. The first is the *push-out mechanism*. An arriving vital cell may enter a saturated queue provided that an ordinary cell is already awaiting transmission. One of the ordinary cells is discarded and the vital cell joins the queue. If the queue contains only vital cells, the arriving vital cell is discarded. On the contrary, ordinary cells cannot enter a saturated queue and are discarded. Since cell sequence must be preserved, the push-out mechanism requires a complicated buffer management logic.

The second solution is the *partial buffer sharing*. When queue occupancy reaches a given threshold, only vital cells may enter the queue. Obviously, this solution is less efficient than the "ideal" push-out mechanism since vital cells can be discarded while ordinary cells are still in the queue, but it is much simpler to implement.

Assessments and comparisons of these solutions, including the route separation, are performed in the following. The performance analysis will be split into two different parts:

- Performance analysis (Section III) and comparison (Section IV) for Poisson input traffic,
  - Performance modeling for bursty input traffic (Section V).
- The first part considers the short-term queueing behavior, whereas the second part deals with the long-term characteristics of the arrival and queueing process [21]. We obtain a very good approximation for the overall queueing behavior by a simple addition of both results [21]. Further, it should be mentioned that the first analysis is useful for dimensioning the network buffers, whereas the second analysis is closely related to the connection admission control within ATM networks.

### III. MODELING SPACE PRIORITIES

This section gives a detailed performance evaluation of different loss priority mechanisms for Poisson input traffic. While much work has been spent on the description and performance evaluation of various time priority mechanisms (see, for example, [18]), there is only little work related to loss priority systems. Recently, queueing systems combining both kinds of priorities have been proposed and studied [1], [12], [16], [27].

Irland [17] has studied different mechanisms for sharing of buffers in store-and-forward switching networks.  $N$  traffic flows, each attached to its own server having an exponentially distributed service time, share a common buffer. This paper deals with a different situation—a single server is attached to the common buffer and the service times are general independent.

Doshi and Heffes [7] have described and analyzed an overload control algorithm using the push-out mechanism with replacement strategy FIFO for the  $M/M/1/N$  queue. Furthermore,

partial buffer sharing policies have been proposed and analyzed as means of overload control [22], [28], [31]. Takagi [31] has analyzed an  $M/G/1/N$  queueing system, where the arrival process is switched off when the buffer limit is reached and switched on again when the buffer occupation falls below a given resume level. Li [22] proposed a similar overload control algorithm, where the upper limit is replaced by an arbitrary value, and he has analyzed this mechanism for  $M/PH/1/N$  and  $PH/M/1/N$  queueing systems. Neuts [28] has analyzed an  $M/G/1$  queueing model with infinite queue capacity and a more sophisticated overload control scheme. Although these mechanisms are related to partial buffer sharing, they do not take into account the "multi-class" aspect of the present problem.

Recently, several papers have analyzed various buffer priority mechanisms using different assumptions [1], [4], [16], [24], [29], [30], [33]. Sumita and Ozawa [30] have provided conservation laws for systems using a push-out scheme. Bonomi *et al.* [1] have outlined an analysis for a partial buffer sharing system which is fed by burst-silence sources (see Section V), whose peak bit rate equals the link bit rate. The classification of the arrivals into Class 1 and Class 2 arrivals is done via a Bernoulli trial. Petr and Frost [29] used geometrically distributed arrivals with the same priority assignment to optimize the thresholds of the partial buffer sharing mechanism. A multiplexing of geometric arrivals (low loss priority) and the above burst-silence sources (high loss priority) using the partial buffer sharing scheme has been presented by Hou and Wong [16]. For simplification, it has been assumed that all Class 1 arrivals are prior to Class 2 arrivals within a given service interval.

Lucantoni and Parekh have analyzed the partial buffer sharing mechanism for Poisson arrivals assuming infinite buffer size [24]. Furthermore, Chang and Wu gave an approximate analysis in [4] for a generalized partial buffer sharing system with deterministic service time, which is fed by Poisson batch arrivals. Moreover, they described and analyzed a push-out scheme where a replacement of cells is only possible for the arrivals within the current service interval. Finally, Yin *et al.* [33] have given an approximate performance analysis for the partial buffer sharing strategy using a fluid flow approximation of burst-silence sources, but they assumed that each source offers precious and ordinary cells simultaneously with a fixed ratio, such that the aggregate arrival rate of Class 1 cells never exceeds the service rate.

The following performance evaluation is valid for Poisson inputs, general independent service times, and a finite waiting room. This has been carried out for two classes of customers, since it is currently the only relevant case for ATM networks [3].

#### A. Traffic Models

The traffic models under consideration are shown in Fig. 1. The arrival process to the queue can be approximated by a memoryless process if a large number of independent traffic sources is assumed and each source contributes a small fraction to the total load. Moreover, the short-term behavior of a statistical multiplexer can be characterized using this simple arrival model [21]. In continuous time systems, this implies a Poisson arrival process. In discrete time systems, the interarrival time between successive arrival instants must be geometrically distributed to obtain this property. An ATM system is basically a discrete time system, but the limiting case of a discrete time  $GEO/G/1$  queueing system is an  $M/G/1$  queueing system and, therefore,

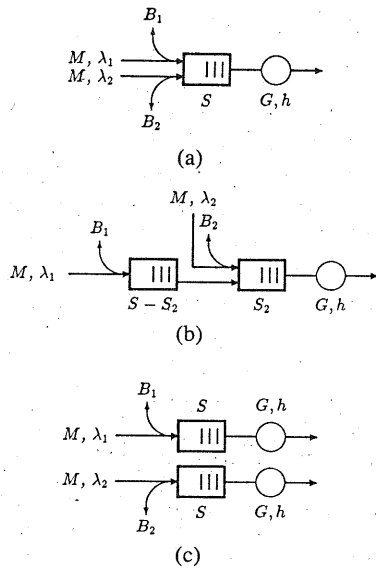


Fig. 1. Space priority mechanisms for selective cell discarding in ATM networks. (a) System using a push-out scheme and a common buffer; (b) System with partial buffer sharing; (c) System with a separate route for each traffic class.

the analysis will be for this continuous time system. Furthermore, we have obtained similar performance results for the equivalent discrete time queueing systems [15].

The service times are independent and generally distributed and have the same distribution for both traffic classes. The service discipline is FIFO, in order to guarantee cell sequence integrity. Additionally, for the push-out mechanism, a strategy has to be defined for pushing out or replacing low priority customers by high priority customers. Throughout this paper, the replacement strategy LIFO is considered because this strategy minimizes the complexity of the buffer management. Using another replacement strategy, for example, RANDOM, results in slightly different loss probabilities [15].

### B. System Using the Push-Out Scheme

The aggregate state process of this system is the same as in the ordinary M/G/1/N queueing system with arrival rate  $\lambda = \lambda_1 + \lambda_2$ , because for every arriving cell which finds the buffer completely occupied, exactly one cell is lost (either the arriving cell itself or the replaced cell). Since all classes have the same service time distribution, a simple conservation law for the aggregate state probabilities and the aggregate loss probability can be stated. The loss probabilities  $B_1$  and  $B_2$  of the two traffic classes are related to the loss probability  $B$  of the ordinary M/G/1/N queueing system with aggregate arrival rate  $\lambda = \lambda_1 + \lambda_2$  in the following way [30]:

$$\lambda_1 B_1 + \lambda_2 B_2 = (\lambda_1 + \lambda_2) B = \lambda B. \quad (1)$$

An extension of this conservation law to more than two traffic classes is straightforward. The stationary characteristics of the M/G/1/N queueing system are well known (see, for example, [13]). Hence, it is sufficient to evaluate the loss probability for one class and to determine the loss probability of the other class from (1).

Therefore, a tagged low priority customer will be observed from joining until leaving the system. From this consideration, the probabilities that this customer will be served can be evaluated. Using the PASTA property (Poisson arrivals, see time averages [32]) and the conservation law for the aggregate steady-state probabilities, the state probabilities observed by an

arriving customer are identical to the steady-state probabilities  $p_k$  (for  $k = 0, 1, \dots, N$ ) of the equivalent M/G/1/N queueing system. The loss probability of Class 2 traffic will be evaluated from the following equation [14]

$$B_2 = \sum_{k=0}^N P_k [1 - P(\text{served} | k)] = 1 - \sum_{k=0}^N P(\text{served}, k) \quad (2)$$

with  $N = S + 1$  being the size of the whole system. The joint probabilities  $P(\text{served}, k)$  that an arriving cell of Class 2 arrives in system state  $k$  and will finally reach service are defined by the following equations for  $k = 0$  and  $k = N$ :

$$P(\text{served}, 0) = p_0 \quad (3)$$

$$P(\text{served}, N) = 0. \quad (4)$$

The remainder of this section deals with the derivation of the other joint probabilities  $P(\text{served}, k)$ .

During an arbitrary service interval,  $n$  customers of the high priority class will arrive with probability

$$A(n) = \int_0^{\infty} \frac{(\lambda_1 t)^n}{n!} \exp(-\lambda_1 t) dH(t) \quad (5)$$

where  $H(t)$  denotes the probability distribution function of the service time.

A customer arriving in queueing position  $k$  will occupy this position for the residual service time of the momentarily served customer. Since Poisson arrivals see time averages, the arriving customer experiences the conditional residual service time of system state  $k$  as the residual service time of the momentarily served customer. Recently, a formula for the mean value of the conditional residual service time in the M/G/1 queueing system has been found [10], [26]. The joint probability that, at an arbitrary moment in an equilibrium period,  $k$  cells are present in the queueing system and the service of the momentarily served cell terminates in the interval  $t, t + dt$  (residual service time) will be denoted by  $r_k(t)$  and has been derived in [20]:

$$r_k(t) = \int_0^{\infty} \lambda h(u + t) \exp(-\lambda u) \cdot \left[ p_0 \frac{(\lambda u)^{k-1}}{(k-1)!} + \sum_{j=0}^{k-1} p_{k-j} \frac{(\lambda u)^j}{j!} \right] du. \quad (6)$$

The joint probability  $A_k(n)$  that an arriving Class 2 cell will arrive in queueing position  $k$  and  $n$  Class 1 customers will arrive until the service of the momentarily served customer can be calculated from the following equation:

$$A_k(n) = \int_0^{\infty} \frac{(\lambda_1 t)^n}{n!} \exp(-\lambda_1 t) r_k(t) dt. \quad (7)$$

The evaluation of these joint probabilities is substantially simplified for a negative exponential service time distribution, where  $r_k(t)$  becomes equal to  $p_k h(t)$  and  $A_k(n) = p_k A(n)$ ;  $h(t)$  is the probability density function of the service time.

Assuming that the tagged cell enters the system in queueing position  $k$  (for  $k = 1, 2, \dots, S$ ), it moves forward to queueing position  $k - 1$  when the service terminates if, during the residual service time of the currently served customer, no more than  $S - k$  customers of the high priority class have arrived. Given that the cell has reached queueing position  $k - j$ , it will be forwarded to queueing place  $k - j - 1$  only if there arrive no more than  $S - k + j$  customers of Class 1 during the initial

residual service time and the following  $j$  service times (this must be conditioned on the constraints, which must be fulfilled to reach queueing place  $k - j$ ). Finally, the service probability is the probability that the customer joins queueing position 0 (server). We establish the following convolution algorithm for the evaluation of the conditional service probability of Class 2 customers. The joint probability that the tagged cell enters the system in queueing position  $k$  and is then able to proceed to queueing position  $k - j - 1$  while  $n$  cells of Class 1 arrive is denoted by  $C_{k,j}(n)$ .

Step 0:

$$C_{k,0}(n) = \begin{cases} A_k(n) & \text{if } 0 \leq n \leq S - k \\ 0 & \text{otherwise.} \end{cases} \quad (8)$$

Step  $j$  ( $1 \leq j \leq k - 1$ ):

$$C_{k,j}(n) = \begin{cases} C_{k,j-1}(n) * A(n) & \text{if } 0 \leq n \leq S - k + j \\ 0 & \text{otherwise.} \end{cases} \quad (9)$$

Final step:

$$P(\text{served}, k) = \sum_{n=0}^{S-1} C_{k,k-1}(n). \quad (10)$$

The operator  $*$  denotes the convolution operation.

customer leaves  $k$  customers behind in the system. According to the previous definition of the partial buffer sharing policy, cells of Class 1 and Class 2 are able to join the queueing system if the system state is less than or equal to  $S$  or  $S_2$ , respectively. Representing the state transitions of the embedded Markov chain by a transition matrix  $Q$  of size  $N \times N$ , the following equation system can be stated, describing the stationary characteristics of the system just after a departure instant:

$$\Pi = \Pi \cdot Q. \quad (11)$$

Since there is a maximum of one customer served between successive embedded points, transitions from level  $k$  to level  $j < k - 1$  are not possible. Transitions between levels  $k \leq S_2$  and  $j \leq S_2$  occur with the total arrival rate  $\lambda$ . The corresponding transition probabilities are denoted by the variables  $q_1(n_1)$  given that  $n_1$  arrivals occur between two successive embedded points. The transitions between levels  $k > S_2$  and  $j > S_2$  depend only on the arrival rate  $\lambda_1$  of Class 1, since the shared part of the buffer is completely occupied under this condition. These transition probabilities will be denoted by  $q_2(n_2)$ , where  $n_2$  describes the number of Class 1 arrivals during one service time. Finally, the remaining transitions consisting of  $n_1$  arrivals with arrival rate  $\lambda$  and  $n_2$  arrivals with arrival rate  $\lambda_1$  occur with the probability  $q_{12}(n_1, n_2)$ . Using these notations, the following transition matrix can be established.

$$Q = \begin{bmatrix} q_1(0) q_1(1) \cdots q_1(S_2 - 1) q_{12}(S_2, 0) & q_{12}(S_2, 1) & \cdots & q_{12}(S_2, S - S_2 - 1) & 1 - \sum_{j=0}^{S_2-1} q_1(j) - \sum_{j=0}^{S-S_2-1} q_{12}(S_2, j) \\ q_1(0) q_1(1) \cdots q_1(S_2 - 1) q_{12}(S_2, 0) & q_{12}(S_2, 1) & \cdots & q_{12}(S_2, S - S_2 - 1) & 1 - \sum_{j=0}^{S_2-1} q_1(j) - \sum_{j=0}^{S-S_2-1} q_{12}(S_2, j) \\ 0 & q_1(0) \cdots q_1(S_2 - 2) q_{12}(S_2 - 1, 0) & q_{12}(S_2 - 1, 1) & \cdots & q_{12}(S_2 - 1, S - S_2 - 1) & 1 - \sum_{j=0}^{S_2-2} q_1(j) - \sum_{j=0}^{S-S_2-1} q_{12}(S_2 - 1, j) \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & q_1(1) & q_{12}(2, 0) & q_{12}(2, 1) & \cdots & q_{12}(2, S - S_2 - 1) & 1 - \sum_{j=0}^1 q_1(j) - \sum_{j=0}^{S-S_2-1} q_{12}(2, j) \\ 0 & 0 & \cdots & q_1(0) & q_{12}(1, 0) & q_{12}(1, 1) & \cdots & q_{12}(1, S - S_2 - 1) & 1 - q_1(0) - \sum_{j=0}^{S-S_2-1} q_{12}(1, j) \\ 0 & 0 & \cdots & 0 & q_2(0) & q_2(1) & \cdots & q_2(S - S_2 - 1) & 1 - \sum_{j=0}^{S-S_2-1} q_2(j) \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & q_2(1) & 1 - \sum_{j=0}^1 q_2(j) \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & q_2(0) & 1 - q_2(0) \end{bmatrix} \quad (12)$$

Using (5)-(7), the arrival probabilities  $A(i)$  and  $A_k(i)$  for high priority cells can be evaluated. Furthermore, the conditional service probabilities are given from (3), (4), and (8)-(10). The loss probability of Class 2 can be calculated from (2) and finally the loss probability of Class 1 is given by the conservation law for the loss probabilities (1).

C. System with Partial Buffer Sharing

The characteristics of this system will be determined using an embedded Markov chain approach. As in the ordinary M/G/1 queueing system, the service completion instants are the embedded points for the underlying Markov chain. Therefore, a probability vector  $\Pi = (\pi_0, \pi_1, \dots, \pi_S)$  is defined, whose  $k$ th component  $\pi_k$  is the probability that a departing cus-

The transition probability  $q_1(n_1)$  is given by

$$q_1(n_1) = \int_0^\infty \frac{(\lambda t)^{n_1}}{n_1!} \exp(-\lambda t) dH(t). \quad (13)$$

The transition probability  $q_2(n_2)$  depends on the arrival rate of Class 1 customers:

$$q_2(n_2) = \int_0^\infty \frac{(\lambda_1 t)^{n_2}}{n_2!} \exp(-\lambda_1 t) dH(t). \quad (14)$$

For transitions from states  $k \leq S_2$  to states  $j > S_2$ , the arrival rate is reduced from  $\lambda$  to  $\lambda_1$  when state  $S_2 + 1$  is reached because all cells of Class 2 are discarded in the overload states. The transition probabilities for these transitions can be computed from the probability distribution function of the time interval containing  $n_1$  arrivals with arrival rate  $\lambda$  and  $n_2$  arrivals

with arrival rate  $\lambda_1$ . This approach leads to an alternating sum (for the given deterministic service time) which tends to numerical instability.

Therefore, a different approach is used to derive numerically stable expressions for the transition probabilities. Assuming a constant arrival rate  $\lambda$  during the whole service time,  $n$  customers will arrive with probability  $q_1(n)$ . After the first  $n_1$  arrivals, each new customer belongs to Class 2 with a probability  $\lambda_2/\lambda$  and will be discarded, because system state  $S_2 + 1$  is exceeded. Therefore, the transition probability  $q_{12}(n_1, n_2)$  is given by the following equation:

$$q_{12}(n_1, n_2) = \sum_{n=n_1+n_2}^{\infty} q_1(n) \binom{n-n_1}{n_2} \left(\frac{\lambda_1}{\lambda}\right)^{n_2} \left(\frac{\lambda_2}{\lambda}\right)^{n-n_1-n_2} \quad (15)$$

The summation can be stopped after a few steps, since the series converges very rapidly.

Assuming an initial value for  $\pi_0$ , the state probabilities may be computed recursively from the equation system (11). One equation is redundant, because it is linearly dependent on the other equations. Finally, the probability  $\pi_0$  is deduced from the probability normalizing condition

$$\sum_{k=0}^S \pi_k = 1. \quad (16)$$

For a derivation of the loss probabilities, it is necessary to determine the probability distribution for the system length encountered by an arrival. This probability distribution is equivalent to the steady-state probability distribution  $p_k$  [32]. The probabilities  $p_k$  (for  $k = 0, 1, \dots, N$ ) must be different from the former departure-point probabilities  $\pi_k$  (for  $k = 0, 1, \dots, N-1$ ), because the state space is enlarged by the state  $N = S + 1$ . For an infinite interval, the number of joining customers equals the number of departing customers. Hence, the effective arrival rate of customers which are able to join the system must be equal to the departure rate:

$$\lambda_1(1 - p_N) + \lambda_2 \left(1 - \sum_{k=S_2+1}^N p_k\right) = \frac{1 - p_0}{h}. \quad (17)$$

A well-known law for the G/G/1 queueing system states that an arriving customer who is able to join the queueing system observes the same state probabilities as a departing customer, given that arrivals and departures occur singly, i.e.,  $\pi_k$  is the state probability seen by a customer who joins the queueing system (see [5] for a proof). Therefore, the following equation holds for the state probabilities just after a departure:

$$\pi_k = \begin{cases} \frac{p_k}{1 - \frac{\lambda_1}{\lambda} p_N - \frac{\lambda_2}{\lambda} \sum_{j=S_2+1}^N p_j} & \text{if } k \leq S_2 \\ \frac{p_k \frac{\lambda_1}{\lambda}}{1 - \frac{\lambda_1}{\lambda} p_N - \frac{\lambda_2}{\lambda} \sum_{j=S_2+1}^N p_j} & \text{if } S_2 < k \leq S. \end{cases} \quad (18)$$

Combining (17) and (18) provides the following steady-state probabilities

$$p_k = \begin{cases} \frac{\pi_k}{\pi_0 + \lambda h} & \text{if } 0 \leq k \leq S_2 \\ \frac{\lambda}{\lambda_1} \frac{\pi_k}{\pi_0 + \lambda h} & \text{if } S_2 < k \leq S \\ 1 - \frac{1}{\pi_0 + \lambda h} \left[ 1 + \frac{\lambda_2}{\lambda_1} \sum_{j=S_2+1}^S \pi_j \right] & \text{if } k = S + 1. \end{cases} \quad (19)$$

The loss probabilities are given as follows:

$$B_1 = p_N \quad (20)$$

$$B_2 = \sum_{k=S_2+1}^N p_k. \quad (21)$$

#### D. System with Route Separation

For a simple network operation, it is assumed throughout the paper that both traffic classes are strictly separated within the network and all buffers have the same size  $S$ . Hence, the queueing model can be split into two different and independent submodels, which can be analyzed using an embedded Markov chain (see, for example, [13]). The same analysis is valid for the system without priorities.

### IV. PRIORITY ASSESSMENT FOR POISSON INPUT

First of all, the loss calculations presented above can be used to give a full characterization of the mechanisms. Unless otherwise stated, the results below are based on the following assumptions.

- Cell loss probability for Class 1 cells ( $B_1$ ) must be less than  $10^{-10}$ .
- Cell loss probability for Class 2 cells ( $B_2$ ) must be less than  $10^{-6}$ .
- The ratio of Class 1 cells is taken as  $\lambda_1/\lambda = 20\%$ .

These assumptions represent a typical ATM traffic mix, in which the Class 1 bearer service is assigned to vital cells which appear in such applications as signaling and subband coded video and require a low loss of information as well as real-time transmission. The corresponding arrival rate ought not to be larger than 15–20% of the total arrival rate. The required cell loss probabilities are given for a single buffer stage (see [6]).

For each of the case studies which follow, the rule is the same. A comparison is given between the four queueing disciplines, namely, no priority (i.e., M/D/1/N), route separation, push-out, and partial buffer sharing, performed as follows.

1) No priority: the multiplexer is modeled as an M/D/1/N queue, where the two flows are indistinctly mixed. The load limitation results from the cell loss constraint of Class 1. That is, the two flows are given the same loss probability  $B_1$ .

2) Route separation: each class feeds a separate M/D/1/N queueing system. The ratio of Class 1/Class 2 traffic is fixed and the total load is limited by the class which reaches the cell loss constraint first. Since the hardware requirements are doubled (two servers, overall buffer size  $2S$ ), the total admissible load is given by the sum of the Class 1 and Class 2 traffic di-

vided by two in order to obtain a fair comparison of the mechanisms. Assuming extremely unbalanced arrival rates, the total admissible load is very low because nearly the whole traffic is carried by one route. Therefore, except for Fig. 3, the ratio of Class 1 and Class 2 traffic is chosen to obtain a maximum for the total load (cell loss constraints reached for both traffic classes).

3) Push-out mechanism: the load is limited by the first of the constraints which is violated. Usually, cells of the other flow (where the constraint is not invoked) have a much lower cell loss probability than admissible.

4) Partial buffer sharing: in this case, the buffer size  $S$  is not sufficient for a dimensioning. Given the loss probabilities  $B_1$  and  $B_2$ , one has to choose  $S_2$  also to maximize the total load. The dimensioning process becomes a more complex trial-and-error game (see below). On the other hand, this allows to adjust more closely the constraints with the actual performances. Two "variants" may be defined, in the first one  $S_2$  is allowed to vary according to the long run traffic fluctuation (adaptive partial buffer sharing); in the second one,  $S_2$  is kept fixed (fixed partial buffer sharing). The robustness of this variant must be estimated.

#### A. Dimensioning Versus Offered Load

The first comparison focuses on the total admissible load as a function of the buffer size. This is the elementary dimensioning process, which points out the merit of using a space priority mechanism.

The curves in Fig. 2 show the kind of results which are to be expected. The first remark is the interest of a space priority scheme. For a given dimensioning, the admissible load is increased. The advantage is made clearer by inverting the argument: for a given load to be carried, the required buffer size decreases.

The second point to be highlighted is the relative equivalence between the push-out and the partial buffer sharing mechanisms. In a large range, both mechanisms achieve the same performance level, the push-out scheme being slightly better. Anyway, in the actual domain of variation, these mechanisms are to be considered as equivalent. The system with route separation provides a smaller gain in a very narrow range of the load ratio  $\lambda_1/\lambda$  (see also Fig. 3).

Table I further illustrates these points for some typical values of the total load, under the given assumptions. The gain provided by space priority schemes can be estimated according to two different criteria: load improvement for a given buffer size or buffer size reduction for a given load.

For the configuration under study, the relative gain on the load to be expected is around 10–15%. Possibly, this is not the most interesting point of view in the sense that other constraints will anyway limit the maximum load. So let us focus on the second aspect: the decrease in buffer size. Table I gives some typical figures.

Recall that for the partial buffer sharing, the Class 2 threshold is assumed to be chosen optimally (i.e., the two thresholds are chosen so that to ensure at the same time the targeted rejection rates). The (relative) superiority of push-out over partial buffer sharing is surprising at first glance, since push-out works almost always by giving a too low rejection probability to one of the flows. The optimality mentioned above does not really favor the partial buffer sharing scheme, because Class 1 flows have to

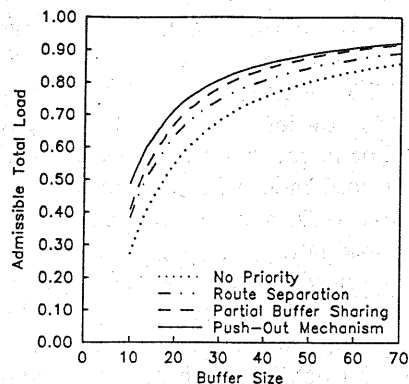


Fig. 2. Admissible total load versus buffer size.

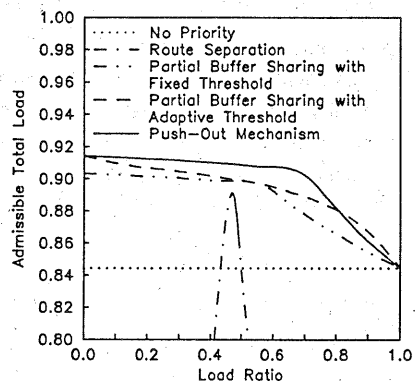


Fig. 3. Admissible total load versus load ratio  $\lambda_1/\lambda$ .

TABLE I  
BUFFER DIMENSIONING FOR VARIOUS PRIORITY MECHANISMS

Total Load	M/D/1/N	Push-Out Mechanism	Partial Buffer Sharing
$\rho = 0.55$	20	12	16
$\rho = 0.70$	32	19	22
$\rho = 0.80$	49	29	31
$\rho = 0.85$	67	38	41

compete with Class 2 in nearly the whole buffer and Class 2 has only access to a fraction of the buffer.

For instance, with a total system size of  $N = 40$ , the following loss probabilities are observed:

- Push-out,  $\rho = 0.85$ , one measures  $B_1 = 1.1 \times 10^{-18}$  and  $B_2 = 7.3 \times 10^{-7}$ ;
- Partial buffer sharing,  $\rho = 0.85$ , one measures for  $S_2 = 36$ :  $B_1 = 3.4 \times 10^{-10}$  and  $B_2 = 1.8 \times 10^{-6}$ ; for  $S_2 = 35$ :  $B_1 = 2.6 \times 10^{-11}$  and  $B_2 = 2.5 \times 10^{-6}$ ;

#### B. Influence of the Class 1/Class 2 Ratio

A second experiment again brings surprising results. For a given dimensioning ( $S$  fixed), let us vary the traffic mix, measured by the ratio  $\lambda_1/\lambda$  or  $\rho_1/\rho$ . Here again, for partial buffer sharing, it is not sufficient to fix the buffer size  $S$ . Two subcases are studied. In the first one (adaptive partial buffer sharing), the threshold  $S_2$  is adjusted to its optimal value. The second scheme (fixed partial buffer sharing), on the other hand, is based on a constant value for the buffer threshold  $S_2$ . The curves (see Fig.

3) are drawn for  $S = 64$ . They show that for the push-out mechanism and for partial buffer sharing in a wide range of the  $\rho_1/\rho$  ratio, the admissible load remains nearly constant. Actually, this is only true for low loss ratios  $B_2/B_1$ , say up to four orders of magnitude. For larger loss ratios, the admissible load decreases with the load ratio  $\rho_1/\rho$ . Due to the assumptions described in Section III-D, route separation is very sensitive to a variation of the load ratio.

The curves presented above show, first of all, the advantage of space priority schemes: increase of admissible load or comparatively easier dimensioning. The results show also the robustness of such a mechanism. There is no need to predict exactly the level of individual components of the traffic, since each of the systems studied is almost independent of the traffic mix. Even for the partial buffer sharing mechanism, an adaptive Class 2 threshold is not of real use.

Whether the push-out mechanism or partial buffer sharing is finally elected, the overall performance will be almost the same. This means that performance criteria are not to be invoked in the choice between push-out and partial buffer sharing. In other words, the latter, which seems more appealing for implementation reasons, seem to be the best candidate for a space priority mechanism.

### C. A Closer Insight into the Partial Buffer Sharing

Once the partial buffer sharing is elected as the feasible space priority mechanism, it remains to study more deeply its characteristics in order to ensure a proper use under various traffic conditions.

First of all, the effect of the Class 2 threshold has to be studied. The curves of Fig. 4 help in answering this question. For a given buffer size (here  $S = 32$ ) and a given load ratio ( $\lambda_1/\lambda = 0.2$ ), the threshold  $S_2$  is varied. The experiment is repeated for various offered loads ( $\rho = 0.6, 0.7$ , and  $0.8$ ). Fig. 4 gives the two loss probabilities  $B_1$  and  $B_2$  (the latter is naturally the higher).

The following properties of the curves can be identified and may be useful for a dimensioning of the threshold  $S_2$ .

- Each of the curves can be approximated by a straight line. This is the usual exponential-like behavior of queueing systems as they reach extreme values [19].
- The point  $S_2 = S$  is the loss probability of the classical M/D/1/N system.
- The curves giving the loss probabilities remain almost parallel as  $\rho$  varies. Moreover, the slope remains almost unchanged as the buffer size varies.

As a consequence, the same ratio  $B_2/B_1$  is attained for similar values of  $S - S_2$  (here,  $B_2/B_1 = 10^4$  for  $S - S_2 = 3$ ). Moreover, the same result holds as  $B$  varies in the domain of interest.

All these remarks may lead to an effective dimensioning procedure. First, given  $(\rho_1, \rho_2)$  and  $(B_1, B_2)$ , the difference  $S - S_2$  is fixed. The dimensioning reduces then in finding the value for  $S$ —this is a one-dimensional process, just like for the push-out mechanism. A similar procedure has been described in [16], whereas Petr and Frost have used stochastic dynamic programming to optimize the buffer thresholds [29].

## V. PERFORMANCE EVALUATION FOR BURSTY INPUT TRAFFIC

If a link in an ATM network carries only a few bursty calls, the Poisson assumption for the arrival process is no longer valid for longer buffers. This implies that the characteristics of each

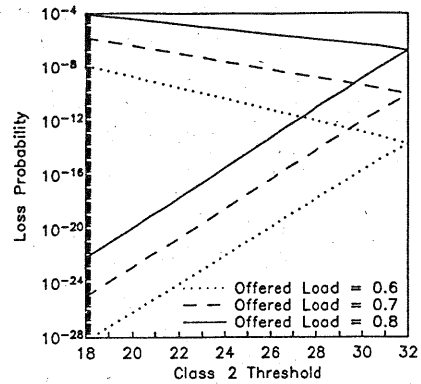


Fig. 4. Loss probability versus threshold of Class 2 (lower curve = Class 1; upper curve = Class 2).

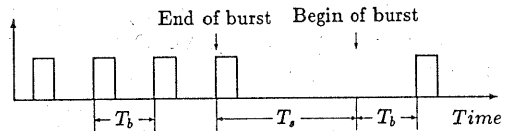


Fig. 5. Sporadic source model.

individual source must be taken into account when dealing with bursty input traffic.

### A. Traffic Model

A sporadic source (burst-silence source) is a realistic ATM traffic source. Such a source emits cells with constant cell interarrival time  $T_b$  if the source is in a burst state and emits no cells if the source is silent (see Fig. 5). The time duration  $T_b$  equals the cell assembly time. The silence duration has a negative exponential distribution with mean value  $T_s$ ; the number of cells within a burst is geometrically distributed and the average number of cells in a burst will be denoted by  $N_b$ .

A voice source is a well-known example of a sporadic source if the coding scheme employs speech activity detection and silence suppression. Further, a data source in interactive data communication can be classified as a sporadic source. The traffic streams originating from different sources will be merged within the ATM network and the aggregate cell arrival process, which substitutes the Poisson arrival process used in Section III, leads to very complex queueing models (see Fig. 1).

### B. Performance Estimation

An exact queueing analysis for the queueing models introduced in Fig. 1, including the given arrival process, seems not tractable and therefore the performance evaluation has to be done by simulation or approximation. Since simulation is only feasible for relatively high cell loss probabilities, a simple approximate analysis will be given in this section.

Usually, traffic models for ATM networks are decomposed into several layers (see, for example, [9]):

- Cell layer,
- Burst layer,
- Call layer.

Congestion may happen in each of these three layers. An overload situation at the call layer leads to call blocking whereas congestion in the lower layers may lead to a loss of cells. In connection with cell loss priorities, only the lower layers must be taken into consideration.



The buffers in an ATM network are designed to resolve congestion at the cell level caused by simultaneously arriving cells. For this purpose, it is sufficient to have short queues (i.e., queue size up to 100 cells) within the ATM network. Buffering whole bursts within the network would require much larger buffers. However, this would degrade the cell delay jitter in an unacceptable way. Hence, an overload situation at burst level cannot be buffered within the network and leads to a loss of cells.

Future VLSI technology will provide buffers which are large enough to cope with a congestion at cell level. The buffer requirements can be estimated using the results for the previous Poisson case, which deals with the short-term queueing behavior [21]. Therefore, we restrict the considerations in this section to the overload at burst level (long-term arrival and queueing characteristics) since this seems to provide a more fundamental limitation of the traffic load for bursty input traffic.

An *upper bound* for the cell loss caused by a congestion at burst level will be derived in the following, neglecting the buffering capabilities of the ATM network at burst level. A similar approach has been used in [23]. A connection of Class  $i$  is in a burst state with probability  $p_{ai} = (N_{bi}T_{bi})/(N_{bi}T_{bi} + T_{si})$  and silent with probability  $1 - p_{ai}$  (the parameters of Class  $i$  are denoted by subscript  $i$ ). The number of sources of Class  $i$  is fixed and is given by  $N_i$ . The probability that  $x_i$  sources of Class  $i$  are in a burst state (are active) can be computed from a binomial distribution:

$$p(x_i) = \binom{N_i}{x_i} p_{ai}^{x_i} (1 - p_{ai})^{N_i - x_i} \quad \forall i = 1, 2. \quad (22)$$

The cell arrival rate, given that  $x_1$  sources of Class 1 and  $x_2$  sources of Class 2 are in an active state, is given by  $x_1/T_{b1} + x_2/T_{b2}$ . The mean aggregate arrival rate can be expressed as  $(N_1 p_{a1})/T_{b1} + (N_2 p_{a2})/T_{b2}$ . Cells will be lost if the total cell arrival rate exceeds the cell service rate  $1/h$ . The aggregate loss rate in a given state  $(x_1, x_2)$  is given by maximum  $(0, x_1/T_{b1} + x_2/T_{b2} - 1/h)$ . With these definitions, the aggregate cell loss probability is given by

$$B = \frac{1}{\frac{N_1 p_{a1}}{T_{b1}} + \frac{N_2 p_{a2}}{T_{b2}}} \sum_{\substack{0 \leq x_1 \leq N_1, \\ 0 \leq x_2 \leq N_2, \\ (x_1/T_{b1}) + (x_2/T_{b2}) > 1/h}} p(x_1)p(x_2) \cdot \left( \frac{x_1}{T_{b1}} + \frac{x_2}{T_{b2}} - \frac{1}{h} \right). \quad (23)$$

In a first step, the loss probability of Class  $i$  will be evaluated without prioritization. The lost cells in a given state  $(x_1, x_2)$  are split up into the two traffic classes, according to the fraction of traffic offered by each class which is given by  $(x_i/T_{bi})/(x_1/T_{b1} + x_2/T_{b2})$  for Class  $i$ . Hence, the following equation for the cell loss probability of Class  $i$  holds:

$$B_i = \frac{1}{\frac{N_i p_{ai}}{T_{bi}}} \sum_{\substack{0 \leq x_1 \leq N_1, \\ 0 \leq x_2 \leq N_2, \\ (x_1/T_{b1}) + (x_2/T_{b2}) > 1/h}} p(x_1)p(x_2) \cdot \left( \frac{x_1}{T_{b1}} + \frac{x_2}{T_{b2}} - \frac{1}{h} \right) \frac{x_i/T_{bi}}{x_1/T_{b1} + x_2/T_{b2}} \quad \forall i = 1, 2. \quad (24)$$

The loss probability of Class 1 will be reduced if a space priority mechanism is introduced. Ideally, cells of the high priority

class will only be lost if an overload situation occurs within this class itself. Hence, the loss probability of Class 1 depends only on the traffic offered by this class:

$$B_1 = \frac{1}{\frac{N_1 p_{a1}}{T_{b1}}} \sum_{\substack{0 \leq x_1 \leq N_1, \\ x_1/T_{b1} > 1/h}} p(x_1) \left( \frac{x_1}{T_{b1}} - \frac{1}{h} \right). \quad (25)$$

The loss probability of Class 2 can be evaluated from the following conservation law for the aggregate loss probability  $B$ :

$$\frac{N_1 p_{a1}}{T_{b1}} B_1 + \frac{N_2 p_{a2}}{T_{b2}} B_2 = \left( \frac{N_1 p_{a1}}{T_{b1}} + \frac{N_2 p_{a2}}{T_{b2}} \right) B. \quad (26)$$

This conservation law is due to the fact that an ideal selective cell discarding mechanism, i.e., the push-out mechanism, decides only which cell will be discarded, but a cell has to be discarded in any case.

This approximation will become asymptotically exact for increasing burst and silence durations if the buffers are large enough to cope with a congestion at cell level. Further, this upper bound for the cell loss probability will also hold for the partial buffer sharing policy, because this mechanism will come close to an ideal selective cell discarding mechanism for the given conditions. Cells are only discarded if an overload at burst level occurs (see results in Fig. 6).

### C. Results

A typical example for a bursty communication service is interactive data or video communication. In data communication, a cell loss can be recovered by a retransmission of cells using appropriate end-to-end protocols. Interactive video communication with modern redundancy reducing coding techniques requires real-time transmission as well as low loss of information. Therefore, data communication will be classified as a service of low loss priority and video communication belongs to the high priority class.

The standardized ATM cell size of 53 bytes leads to a transmission time  $h$  of a cell equal to  $2.827 \mu\text{s}$  at a transmission rate of  $150 \text{ Mb/s}$ . The peak bit rate of both classes is assumed to be  $10 \text{ Mb/s}$ . Further, the burstiness of the video source is assumed to be 2.7 (from measurements performed at CNET; similar values are given in [25]) and the burstiness of interactive data communication (or video retrieval) is assumed to be 5 [11]. The parameters of both classes are summarized in Table II. For the video source, the sum of average burst and silence period equals the frame duration (40 ms in Europe). The time duration of burst and silence periods are chosen relatively short in order to obtain stable simulation results. If these time durations will be longer, the simulation results will approach the approximation results [21].

The simulation is performed for the partial buffer sharing mechanism with the parameters  $S = 64$  and  $S_2 = 48$ . In Fig. 6, the admissible number of Class 1 and Class 2 connections is shown for allowed cell loss probabilities of  $B_1 = 10^{-4}$  and  $B_2 = 10^{-2}$ . Without prioritization, the cell loss probability for all connections must be kept below  $10^{-4}$ . The admissible region is convex for this case. However, if priorities are used, the admissible region may become concave as indicated in Fig. 6. Hence, an approximation of the admissible region by its tangent is too optimistic for means of call admission control. It should be emphasized that the simulation results approach the bound given by the approximation, even for relatively short burst and silence durations.

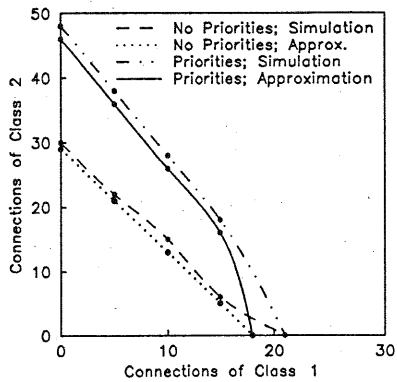


Fig. 6. Admissible number of Class 1 and Class 2 connections.

TABLE II  
INPUT PARAMETERS FOR BOTH TRAFFIC CLASSES

	Mean Burst Duration $N_b T_b$	Mean Silence Duration $T_s$	Cell Interarrival Time $T_b$
Class 1	14.815 ms	25.185 ms	38.4 $\mu$ s
Class 2	100 ms	400 ms	38.4 $\mu$ s

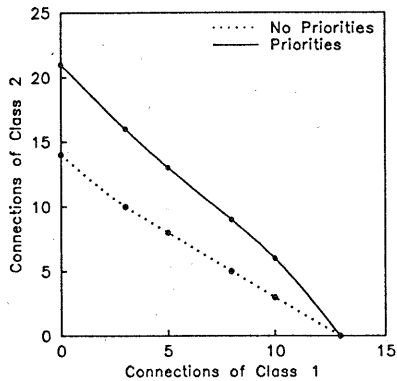


Fig. 7. Admissible number of Class 1 and Class 2 connections.

Finally, the load improvement is studied for realistic values of the loss probability per buffer ( $B_1 = 10^{-10}$ ,  $B_2 = 10^{-6}$ ). The approximation results in Fig. 7 indicate a significant load improvement if the traffic contribution of Class 2 is substantial. This is due to the fact that the load for bursty input traffic is much lower than the load for Poisson input traffic. This offers the opportunity for a significant load improvement in ATM networks given that the quality of the cell transfer is adapted to the QOS characteristics of the corresponding B-ISDN services.

## VI. CONCLUSION

The definition of a second bearer capability in the ATM network introduces a fundamental flexibility: an application pays for the transfer quality it actually requires. Besides a high-quality transfer providing for a "quasi-zero" cell loss rate, a medium-quality transfer could be defined which would partially relax this cell loss requirement.

We have investigated the introduction of a second bearer capability providing for a  $10^{-6}$  cell loss rate instead of  $10^{-10}$ . Because of mathematical tractability, the cell arrival process has been assumed to be Poisson for both bearer capabilities in the performance evaluation. In this case, the multiplex load is not severely limited by a unique high-quality transfer—the maximum admissible load is 0.844 for a buffer size of 64 cells. With such a high starting point, it is clear that an impressive

improvement of the multiplex load cannot be expected. However, it has been assessed to a value around 8%, which represents still a lot of traffic on a high-speed link and indicates a deep modification of the traffic handling since percents are very difficult to gain when the load is ranging between 0.85 and 0.95. The push-out mechanism achieves the highest load improvement. Indeed, it represents the "ideal" behavior of a door-keeper sorting vital and ordinary cells among the arrival flow. However, the partial buffer sharing mechanism provides for very close performances and should be preferred since it is far simpler to implement.

This improvement could also be obtained by doubling the buffering capability of the switching elements, which will be feasible very soon without increasing the cell end-to-end delay. Actually, the basic advantage of a selective discarding mechanism is that it makes the network robust enough to cope with bursty traffic, a property which cannot be achieved by any practical overdimensioning. In most cases, a queue located somewhere in the ATM transit network is multiplexing the traffic streams of several hundred traffic sources so that the Poisson statistics can be used to model the cell arrival process and assess the queue buffering capability. However, it may happen that this queue will have to multiplex a few tens of bursty sources. Even if the multiplex load constraint is respected, transient queue saturations are to be expected more frequently since the offered traffic is more variant than Poisson. By means of a second bearer capability and a selective discarding mechanism, the network can decide which cells are to be discarded first when a congestion occurs. If vital cells are saved from loss, this congestion can be made up by the ATM adaptation layer at the receiving side. We have presented an approximation for the network behavior under such traffic conditions, recognizing that further studies are required.

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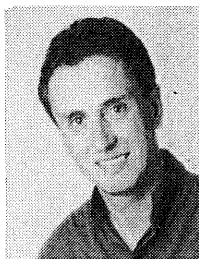
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