

Buffer Dimensioning in ATM Networks Using No-priority and Pushout Space Priorities

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Abstract

Because of the statistical multiplexing of a large number of sources in an ATM network, it is not possible to eliminate cell losses due to buffer overflows. Several space priority mechanisms have been proposed in the literature to manage buffers in the case of congestion. The aim of this paper is to establish buffer dimensioning criteria for the no-priority and the pushout space priority schemes under a broad range of input traffic parameters for a given QoS requirement. Analytical models have been developed to enable the study under very low cell loss probabilities.

Key Words: Space priority, ATM systems, congestion control, buffer management.

1 Introduction

Because of the statistical multiplexing, congestion may arise in an ATM network due to the peak rate of different sources to overlap in time. This could lead to the possibility of cells being lost inside the network. To ease the decision regarding the cell to be dropped in the case of congestion, the cells in an ATM network are classified as high priority (Class 1) and low priority (Class 2).

Different approaches have been proposed in the literature to meet the QoS requirements in the case of congestion in an ATM switch buffer. The approaches differ in their performance, resource requirement and implementation complexity. In this study, we compare the resource requirement for the no-priority and pushout space priority mechanisms to drop cells in the case of congestion in an ATM switch buffer. The *no-priority* scheme is non-preemptive in nature and drops incoming cells whenever the buffer is full. If the buffer has i empty spaces and the number of incoming cells is j , $j > i$, it randomly accepts i cells from the incoming cells. Amongst all the space priority mechanisms proposed to control congestion, the no-priority scheme is the simplest to implement. The *pushout* scheme [1] is a preemptive technique where an arriving Class 1 cell can push out a Class 2 cell (except the one in service) from the buffer. Its implementation complexity is greater than the no-priority scheme but results in a lower cell loss rate for Class 1 cells. It requires smaller buffer size than the no-priority scheme for the same QoS requirements. The analysis of space priority mechanisms have, in most cases, been studied with the *average* number of cells in a buffer under different input loads [2], *loss probability* of cells [3, 4, 5], and maximum *admissible* load, defined as the maximum input load that can be offered to maintain a certain QoS [2, 3, 5, 6]. The *aim* of this paper is to study quantitatively the buffer requirements for the no priority and the push out space priority schemes under different QoS requirements. The objectives of this study are:

- buffer *dimensioning*, i.e., determining the required buffer size for the priority schemes under the same loss requirements,
- to accurately assess the *performance* of an ATM switch using the no priority and pushout space priority schemes, and
- to evaluate the relative *effectiveness* of the pushout via comparison with the no-priority scheme,

The assumptions and notations under which we develop the model are presented in Sections 2 and 3 followed by the model in Section 4. Results obtained from the model are discussed in Section 5, and finally some concluding remarks in Section 6.

2 System Operating Assumptions

We will assume a non-blocking ATM switch with N inputs and N outputs. Each output of the switch has a buffer associated with it. The assumptions under which the model has been developed are similar to [7] and are briefly given below.

1. The switch operates synchronously.
2. Each buffer can hold upto B cells, and is *fast* enough to accept upto N cells per cycle.
3. *Enqueueing* and *dequeueing* of cells in a buffer take place during the same clock cycle.
4. The *service* discipline of the buffer is FIFO.
5. Cell arrivals at the different switch inputs are *statistically independent*. Cell arrival at each input of the switch is an i.i.d. *Bernoulli* process.
6. We assume *two classes* of traffic. Class 1 and Class 2 traffic are the loss sensitive (high priority) and the loss insensitive (low priority) traffic respectively.

In the no priority scheme, if the number of cells destined to a particular buffer is less than the number of empty spaces in the buffer, cells are chosen at *random* (from the arriving cells) for being queued at the buffer. In the pushout scheme, if the number of cells destined to a buffer is more than the empty spaces, Class 1 cells are given priority in accessing the buffer. Moreover, a Class 1 cell can push out a Class 2 cell from the buffer. When a Class 2 cell has to be pushed out of a buffer, the Class 2 cell closest to the head of the queue is pushed out [8]. A Class 1 cell can be dropped at the input of the switch if there is no Class 2 cell which can be pushed out from the destined buffer.

3 Notations

N = Size of the switch.

$p(i, j, N)$ = Probability of i Class 1 and j Class 2 cells arriving at a buffer of an $N \times N$ switch during a cycle.

h = Probability that a cell arriving at a switch input is of Class 1. Therefore, $1 - h$ is the probability of the arriving cell being of Class 2.

B = Size of the buffer at a switch output.

L'_2 = Loss probability of a Class 2 cell at a switch input.

L''_2 = Loss probability of a Class 2 cell from the buffer. This is the probability that a Class 2 cell is pushed out of the buffer by a Class 1 cell. This is applicable only in the case of pushout scheme.

L_1 = Loss probability of a Class 1 cell. Class 1 cells can only be lost at the switch inputs.

$L_2 = L'_2 + L''_2$ = Loss probability of a Class 2 cell.

$\pi_{i,j}$ = Steady state probability of a buffer containing i Class 1 and j Class 2 cells.

π_k = Steady state probability of a buffer containing a total of k cells, i.e., $\pi_k = \sum_{i=0}^k \pi_{i,k-i}$.

$(a)^+$ = Maximum of 0 and a .

$(a, b)^-$ = Minimum of a and b .

4 The Model

The model developed in this paper is based on the Markov chain approach as used by other authors [2]. All the buffers are assumed to be identical; hence we analyze only one buffer. Let the state of a buffer be represented by a tuple (x, y) , $0 \leq x + y \leq B$, where x and y are the number of Class 1 and Class 2 cells in the buffer respectively. At the end of the forward phase, the intermediate state is $(x-1, y)$ or $(x, y-1)$ depending on whether a Class 1 or Class 2 cell leaves the buffer. The probability of i Class 1 and j Class 2 cells arriving at a buffer is given by

$$p(i, j, N) = \binom{N}{i+j} \binom{i+j}{i} \left(\frac{p}{N}\right)^{i+j} \left(1 - \frac{p}{N}\right)^{N-i-j} h^i (1-h)^j$$

The transition probability from state (x, y) to (u, v) will be represented by $\tau_{x,y}^{u,v}$. The transition matrix \mathbf{T} is therefore given by

$$\mathbf{T} = \begin{bmatrix} \tau_{0,0}^{0,0} & \tau_{0,0}^{0,1} & \tau_{0,0}^{1,0} & \cdots & \tau_{0,0}^{B-1,1} & \tau_{0,0}^{B,0} \\ \tau_{0,1}^{0,0} & \tau_{0,1}^{0,1} & \tau_{0,1}^{1,0} & \cdots & \tau_{0,1}^{B-1,1} & \tau_{0,1}^{B,0} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tau_{B-1,1}^{0,0} & \tau_{B-1,1}^{0,1} & \tau_{B-1,1}^{1,0} & \cdots & \tau_{B-1,1}^{B-1,1} & \tau_{B-1,1}^{B,0} \\ \tau_{B,0}^{0,0} & \tau_{B,0}^{0,1} & \tau_{B,0}^{1,0} & \cdots & \tau_{B,0}^{B-1,1} & \tau_{B,0}^{B,0} \end{bmatrix}$$

4.1 State Transition - No Priority

In this section, we compute the elements of the state transition matrix \mathbf{T} for the no-priority scheme. The equations are different depending on whether the initial state is $(0,0)$, the buffer is full, and various combinations of initial and final states. The different cases are given below.

Case N0: $(u + v < x + y - 1) \vee (u < x - 1) \vee (v < y - 1)$

$$\tau_{x,y}^{u,v} = 0$$

Case N1A: $(x = y = 0) \wedge (u + v < B)$

$$\tau_{x,y}^{u,v} = p(u, v, N)$$

Case N1B: $(x = y = 0) \wedge (u + v = B)$

$$\tau_{x,y}^{u,v} = \sum_{j=v-y}^{N-(u-(x-1)^+)} \sum_{i=u-(x-1)^+}^{N-y} p(i, j, N) \frac{\binom{i}{u-(x-1)^+} \binom{j}{v-y}}{\binom{i+j}{u-(x-1)^+ + v-y}}$$

Case N2A: $\overline{(x = 0) \wedge (y = 0)} \wedge (u + v < B)$

$$\tau_{x,y}^{u,v} = \frac{x}{x+y} p(u-x+1, v-y, N) + \frac{y}{x+y} p(u-x, v-y+1, N)$$

Case N2B: $\overline{(x = 0) \wedge (y = 0)} \wedge (u + v = B)$

$$\tau_{x,y}^{u,v} = \frac{x}{x+y} \sum_{j=v-y}^{N-(u-(x-1)^+)} \sum_{i=u-(x-1)^+}^{N-j} p(i, j, N) \frac{\binom{i}{u-(x-1)^+} \binom{j}{v-y}}{\binom{i+j}{u-(x-1)^+ + v-y}} + \frac{y}{x+y} \sum_{i=u-x}^{N-(v-(y-1)^+)} \sum_{j=v-(y-1)^+}^{N-i} p(i, j, N) \frac{\binom{i}{u-x} \binom{j}{v-(y-1)^+}}{\binom{i+j}{u-x+v-(y-1)^+}}$$

Note that in the above equations, the result of a summation is zero if the lower limit is negative, i.e., $\sum_{w=w_1}^{w_2} = 0$ if $w_1 < 0$.

4.2 State Transition - Pushout

In this section, we compute the elements of the state transition matrix \mathbf{T} for the pushout scheme. The equations, depending on whether the initial state is $(0,0)$, the buffer is full, and various combinations of initial and final states, are given below.

Case P0: $(u + v < x + y - 1) \vee (u < x - 1)$

$$\tau_{x,y}^{u,v} = 0$$

Case P1A: $(x = y = 0) \wedge (u + v < B)$

$$\tau_{x,y}^{u,v} = p(u, v, N)$$

Case P1B-a: $(x = y = 0) \wedge (u + v = B) \wedge (v > 0)$

$$\tau_{x,y}^{u,v} = \sum_{j=(v)^+}^{N-(u-(x-1)^+)} p(u-(x-1)^+, j, N)$$

Case P1B-b: $(x = y = 0) \wedge (u + v = B) \wedge (v = 0)$

$$\tau_{x,y}^{u,v} = \sum_{j=(v-y)^+}^{N-(u-(x-1)^+)} \sum_{i=u-(x-1)^+}^{N-j} p(i, j, N)$$

Case P2A-a: $\overline{(x = 0) \wedge (y = 0)} \wedge (u + v < B) \wedge (u < x)$

$$\tau_{x,y}^{u,v} = p(u-(x-1)^+, v-y, N)$$

Case P2A-b: $\overline{(x = 0) \wedge (y = 0)} \wedge (u + v < B) \wedge (v < y)$

$$\tau_{x,y}^{u,v} = p(u-x, v-(y-1)^+, N)$$

Case P2A-c: $\overline{(x = 0) \wedge (y = 0)} \wedge (u + v < B) \wedge (u \geq x) \wedge (v \geq y)$

$$\tau_{x,y}^{u,v} = \frac{x}{x+y} p(u-(x-1)^+, v-y, N) + \frac{y}{x+y} p(u-x, v-(y-1)^+, N)$$

Case P2B-a: $\overline{(x=0) \wedge (y=0)} \wedge (u+v=B) \wedge (u < x)$

$$\tau_{x,y}^{u,v} = \sum_{j=(v-y)^+}^{N-(u-(x-1)^+)} p(u-(x-1)^+, j, N)$$

Case P2B-b: $\overline{(x=0) \wedge (y=0)} \wedge (u+v=B) \wedge (u \geq x) \wedge (v > 0)$

$$\tau_{x,y}^{u,v} = \frac{x}{x+y} \sum_{j=(v-y)^+}^{N-(u-(x-1)^+)} p(u-(x-1)^+, j, N) + \frac{y}{x+y} \sum_{j=(v-(y-1)^+)^+}^{N-(u-x)} p(u-x, j, N)$$

Case P2B-c: $\overline{(x=0) \wedge (y=0)} \wedge (u+v=B) \wedge (u \geq x) \wedge (v=0)$

$$\tau_{x,y}^{u,v} = \frac{x}{x+y} \sum_{j=(v-y)^+}^{N-(u-(x-1)^+)} \sum_{i=u-(x-1)^+}^{N-j} p(i, j, N) + \frac{y}{x+y} \sum_{i=u-x}^{N-(v-(y-1)^+)^+} \sum_{j=(v-(y-1)^+)^+}^{N-i} p(i, j, N)$$

4.3 Steady State Probabilities

The steady state probability of a buffer is computed by solving the set of Markov chain equations.

$$\mathbf{\Pi} = \mathbf{\Pi T}$$

where $\mathbf{\Pi} = [\pi_{0,0}, \pi_{0,1}, \pi_{1,0}, \pi_{0,2}, \pi_{1,1}, \pi_{2,0} \dots \pi_{B-1,1}, \pi_{B,0}]$ is the set of steady state probabilities of a single buffer. Therefore, the steady state buffer occupancy $\pi_k, k = 0 \dots B$, is given by $\pi_k = \sum_{i=0}^k \pi_{i,k-i}$.

4.4 Cell loss probabilities: No-priority

For the no-priority scheme, both Class 1 and Class 2 cells can be lost at the switch inputs due to buffers being full. For the no-priority, the loss probability of a Class 1 and Class 2 cell at a *switch input* are given by

$$L_1 = \sum_{\text{all } m,n \in \Pi} \sum_{i=0}^N \sum_{j=0}^{N-i} \pi_{m,n} p(i, j, N) \left[\frac{m}{m+n} ((i+j) - (B - (m-1) - n))^+ \frac{i}{i+j} + \frac{n}{m+n} ((i+j) - (B - m - (n-1)))^+ \frac{j}{i+j} \right]$$

$$L_2 = \sum_{\text{all } m,n \in \Pi} \sum_{i=0}^N \sum_{j=0}^{N-i} \pi_{m,n} p(i, j, N) \left[\frac{m}{m+n} ((i+j) - (B - (m-1) - n))^+ \frac{j}{i+j} + \frac{n}{m+n} ((i+j) - (B - m - (n-1)))^+ \frac{j}{i+j} \right]$$

4.5 Cell loss probabilities: Pushout

For the pushout scheme, in addition to cell losses at the switch inputs, Class 2 cells can be pushed out of buffers by arriving Class 1 cells. The loss probability of a Class 1 or a Class 2 cells at a *switch input* is given by

$$L_1 = \sum_{\text{all } m,n \in \Pi} \sum_{i=0}^N \sum_{j=0}^{N-i} \pi_{m,n} p(i, j, N) \left[\frac{m}{m+n} (i - (B - (m-1)^+))^+ + \frac{n}{m+n} (i - (B - m))^+ \right]$$

$$L_2 = \sum_{\text{all } m,n \in \Pi} \sum_{i=0}^N \sum_{j=0}^{N-i} \pi_{m,n} p(i, j, N) \left[\frac{m}{m+n} (j - (B - (m-1)^+ - n - i))^+ + \frac{n}{m+n} (j - (B - (n-1)^+ - m - i))^+ \right]$$

Loss probability of a Class 2 cell being pushed out of a buffer by an arriving Class 1 cell is given by

$$L'_2 = \sum_{\text{all } m,n \in \Pi} \sum_{i=0}^N \sum_{j=0}^{N-i} \pi_{m,n} p(i, j, N) \left[\frac{m}{m+n} (n, (i - (B - (m-1)^+ - n))^+)^- + \frac{n}{m+n} (n, (i - (B - (m-1)^+ - n))^+)^- \right]$$

5 Results

Based on CCITT recommendations for QoS requirements for the B-ISDN, end-to-end cell loss probabilities of 10^{-8} and 10^{-3} have been considered for video communications and telephony respectively [9]. Assuming 100 switches between an end to end connection, cell loss probabilities of 10^{-10} and 10^{-5} are required for Class 1 and Class 2 traffic. We therefore assume cell loss probabilities of 10^{-10} and 10^{-5} for Class 1 and Class 2 traffic as an acceptable QoS for this study.

Figure 1 shows the cell loss probability (at a switch input) under the no priority scheme. The loss probability is the same for both the classes, and the probability decreases with an increasing buffer size and increases with an increasing load at the input of the switch. In the no priority scheme, a cell loss probability of 10^{-10} for both the classes of traffic has to be maintained in order to satisfy the Class 1 loss requirements as mentioned above. From Figure 1, we find that the buffer sizes required to maintain the above loss probabilities are 7.3, 11.2 and 18.3 for input loads of 0.2, 0.4 and 0.6 respectively. The buffer size requirements are rounded up to the nearest integer in Table 1.

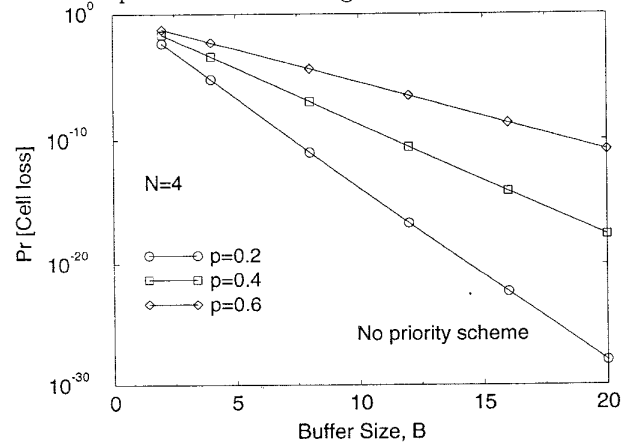


Figure 1: Cell loss probabilities for the no priority scheme.

Figures 2, 3 and 4 show the cell loss probabilities for the push out scheme for input loads of 0.2, 0.4 and 0.6 respectively. The buffering requirements are obtained by taking the maximum of the buffer sizes required to maintain cell loss requirements of 10^{-10} and 10^{-5} for Class 1 and Class 2 traffic respectively. The required buffer sizes for various input loads are shown in Table 2 for $h = 0.2$ and 0.4 . For example, (4.85, 3.88) in the table means that buffer sizes of 4.85 and 3.88 are required to maintain cell loss probabilities

Table 1: Buffer requirements in the no priority scheme for a cell loss probability of 10^{-10} for Class 1 and Class 2 traffic.

Input load, p	Buffer size, B
0.2	8
0.4	12
0.6	19

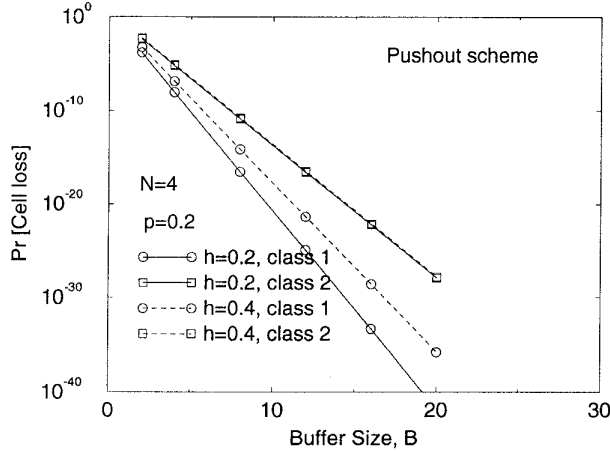


Figure 2: Cell loss probabilities in the pushout scheme for $p = 0.2$.

of 10^{-10} and 10^{-5} for Class 1 and Class 2 traffic respectively. The implementable buffer size is obtained by taking the maximum of the two requirements and rounding up to the nearest integer.

From Table 2, we observe that for large values of h ($h = 0.4$), the buffer size is determined by the Class 1 traffic requirements. For small values of h ($h = 0.2$), the required buffer size may be dictated by the Class 2 requirement if the input load is high (for example, $h = 0.6$). In general, Class 2 traffic requirements become important as the input load increases. On the other hand, the Class 1 traffic requirement becomes important when the proportion of Class 1 traffic (h) increases.

It is interesting to observe in Figure 5 the Class 1 and Class 2 cell loss probabilities at the switch inputs (L_1, L'_2)

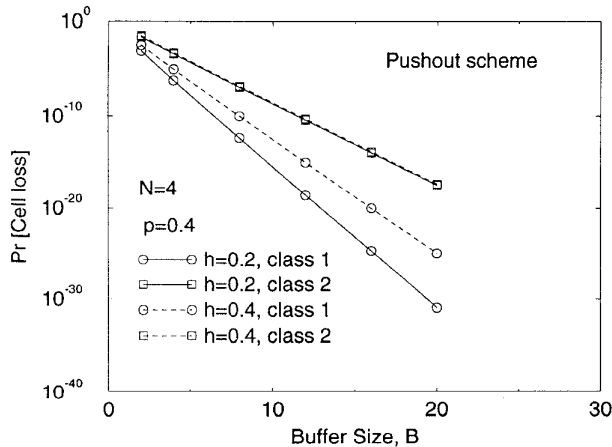


Figure 3: Cell loss probabilities in the pushout scheme for $p = 0.4$.

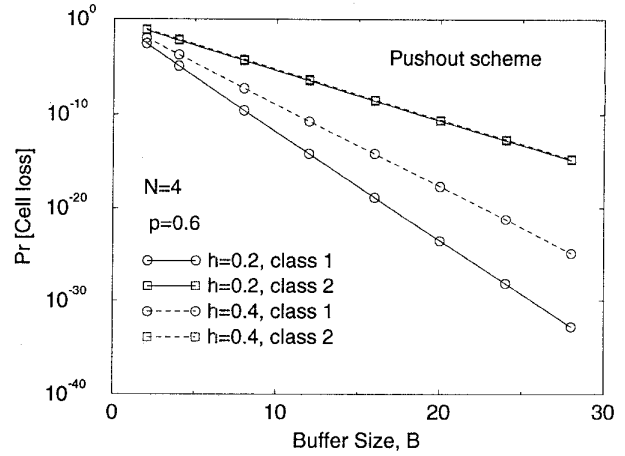


Figure 4: Cell loss probabilities in the pushout scheme for $p = 0.6$.

Table 2: Buffer requirements for the pushout scheme for cell loss probabilities of 10^{-10} and 10^{-5} for Class 1 and Class 2 traffic respectively.

$h = 0.2$	
Input load, p	Buffer size, B
0.2	$\lceil \max(4.85, 3.88) \rceil = 5$
0.4	$\lceil \max(6.4, 5.7) \rceil = 7$
0.6	$\lceil \max(8.2, 8.9) \rceil = 9$

$h = 0.4$	
Input load, p	Buffer size, B
0.2	$\lceil \max(5.6, 3.9) \rceil = 6$
0.4	$\lceil \max(7.9, 5.8) \rceil = 8$
0.6	$\lceil \max(11, 9.3) \rceil = 11$

and the Class 2 cell loss probability at the buffer (L'_2) due to pushout. The Class 2 cell loss probability at a switch input and at a buffer are almost the same. The average number of cells in a buffer (*buffer occupancy*) as a function of the input load is shown in Figure 6 for $N = 4$, $B = 16$ and $h = 0.4$. The average amount of buffer space occupied by Class 1 and Class 2 traffic is also shown. It is seen that the buffer occupancy increases dramatically as the input load exceeds 0.7. The Class 1, Class 2 and the overall buffer occupancy as a function of the proportion of the Class 1 traffic is shown in Figure 7 for for $N = 4$, $B = 16$ and $p = 0.4$. The total buffer occupancy is 0.5 and the buffer space is divided among the Class 1 and Class 2 traffic in the same proportion (h) as in the input traffic. This is because of sufficient buffer space ($B = 16$) for an input load of 0.4. However, when the buffer space is small, the proportion of buffer space occupied by the Class 1 traffic is more than the proportion of the Class 1 traffic in the input load, as seen in Table 3. The smaller the buffer size, the higher is the proportion of the Class 1 traffic occupying the buffer space for the same value of h . In the case of small buffer space, Class 2 cells are pushed out to make room for the Class 1 traffic.

6 Conclusions

We have presented analytical models to compare the performance of the no-priority and the pushout space priority schemes. The model has enabled us to study the buffer dimensioning problem. It is found that for practical cell loss

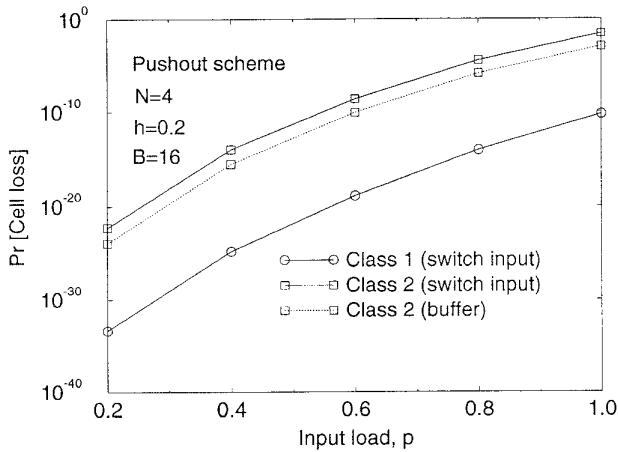


Figure 5: Cell loss probabilities at the switch inputs and the buffers for different input loads.

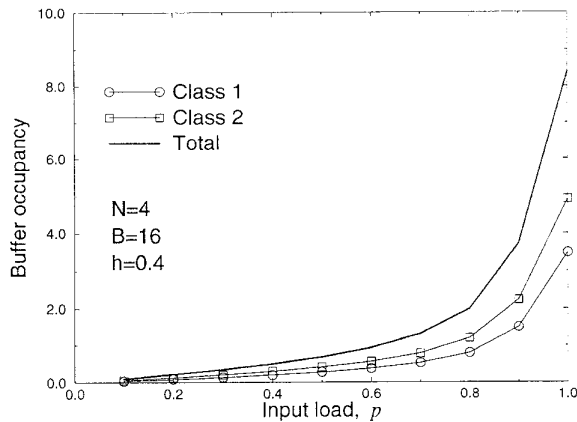


Figure 6: Buffer occupancy for Class 1 and Class 2 traffic as a function of the input load.

requirements, the required buffer size in the pushout scheme is almost half that required in the no-priority scheme. We have also shown that for large proportions of Class 1 traffic, the required buffer size is dictated by the Class 1 buffer size requirement. Class 2 buffer size requirement is the influencing factor in the dimensioning problem for high values of input traffic load and small proportion of Class 1 traffic. The model can be used by switch designers to study the buffering requirements at a switch under different operating environments.

Acknowledgement

The work reported in this paper was partially funded by Telestra, Siemens, Monash University and the Research Data Network CRC.

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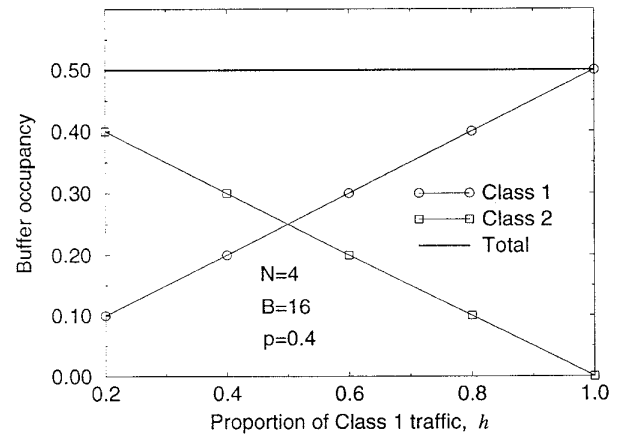


Figure 7: Buffer occupancy for Class 1 and Class 2 traffic as a function of the proportion of Class 1 traffic.

Table 3: Fraction of buffer space occupied by Class 1 traffic for different proportions of Class 1 traffic.

h	$B = 2$	$B = 8$	$B = 16$
0.2	0.244737	0.214495	0.207846
0.4	0.474065	0.428810	0.415692
0.6	0.678291	0.639712	0.623247
0.8	0.853512	0.834758	0.824505
1.0	1.000000	1.000000	1.000000

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