# ATM Traffic Management With Diversified Loss and Delay Requirements *


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## Abstract

*One of the most challenging problems in ATM network design is providing diversified Quality of Service (QoS) to applications with distinct characteristics. A flexible priority service policy for two applications (classes) with strict - and in general distinct - deadlines and different deadline violation rates (loss rates) is studied in this paper. The proposed policy is a generalization of the Shortest Time to Extinction (STE) policy (or the Early-Due-Date policy which discards expired cells). The relationship of this policy to other standard ones is also discussed. Performance measures such as cell loss, mean cell-delay and the tail of the cell-delay probability distribution are derived for each class. Numerical results illustrate the effectiveness of the studied priority scheme. Finally, a low-complexity implementation scheme is proposed, which does not require time-stamp-based sorting.*


## 1 Introduction

Asynchronous Transfer Mode (ATM) has been selected as the CCITT standard for the switching and multiplexing technique of the future Broadband-Integrated Service Digital Networks (B-ISDN). These networks are expected to support services with diversified traffic characteristics and Quality of Service (QoS) requirements. To efficiently utilize the network resources through statistical multiplexing while providing the required QoS to the supported applications, it is necessary that the service to a specific application be dependent on its QoS requirement. As a result, some type of priority service needs to be adopted to provide for the diversification in the QoS provided to different applications.

A priority service scheme can be defined in terms of a policy determining: (a) which of the arriving cells are admitted to the buffer(s); and/or (b) which of the admitted cells is served next. The former priority service schemes are typically refered to as "space-priority" schemes and impact substantially on the delivered cell loss metric. The latter are typically referred to as "time-priority" (or priority-scheduling) schemes and impact substantially on the delivered cell delay metric. Most of the priority service schemes proposed and studied in the past can be classified as either space-priority or time-priority; in these cases, the QoS is typically defined in terms of a cell loss constraint or cell delay constraint, respectively. Recently, some attempts to incorporate both space- and time- priority policies to deliver diversified service defined in terms of both a cell loss and cell delay constraints, have been reported.

An interesting policy called Head-of-the-Line with Priority Jumps (HoL-PJ) is proposed in [5]. By setting properly the priority jumping parameters, this policy gives priority to the packet with the largest queueing delay in excess of its delay deadline and, thus, it becomes the Early-Due-Date (EDD) policy [7]. As emphasized in [5], the HoL-PJ policy provides for a mechanism to implement the EDD policy without requiring the additional processing delay and complexity necessary to identify the next packet to be served under the classical EDD policy. The priority policy considered in the present paper has some similarities to the HoL-PJ policy. As it will be indicated in the next section, the objectives and evaluated performance measures associated with the present study are different. Furthermore, the proposed policy may be viewed as a generization to the Shortest-Time-to-Extinction (STE) [7] in a similar way that the HoL-PJ policy may be viewed as a generalization of the EDD policy. The EDD policy which discards packets which have violated their deadlines has been called the Shortest-Time-to-Extinction (STE) policy in [7]. As it has been shown in [7] and [8], this policy minimizes the number of packets which miss their deadline.

In [3], a queue management scheme is proposed for ATM switches, under multiple cell delay and cell loss QoS requirements; the non-flexible Head-of-Line priority is considered to deliver the cell delay requirements and a push-out scheme is considered for cell loss management. Another approach is presented in [6], where the Self-Calibrating Push-out and Early-


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Due-Date policies are assumed for cell loss and cell delay control, respectively. Cell loss and cell delay performance have also been investigated in the priority service scheme considered in [4]: a Weighted-Fair-Queueing and Buffer Threshold combination. It turns out that the delay bounds computed in [4] are loose because the buffer size cannot accurately reflect the cell delay in this service scheme.

In some real-time applications a strict delay deadline may be associate with its QoS requirement; cells which are delayed beyond the deadline are considered to be lost. For such applications the QoS would be defined in terms of the acceptable maximum cell delay and the acceptable maximum cell loss probability, where the latter is defined - in this case - as the probability of delay-deadline violation. This cell loss probability is controllable by a time-priority policy, rather than a space-priority one controlling losses due to buffer-space limitations. Although cell losses may also occur due to buffer space limitations, it may be assumed that discarded cells due to space limitations have already violated their deadline and, thus, such losses have already been "registered". In fact, an effective priority service policy for different classes of delay-constrained applications, would be one which minimizes the cell delay violation probability and discards (does not serve) the violating cells. The policy proposed here generalizes the STE policy - in the sense that the STE policy corresponds to a specific setting of some parameter - and is capable of providing the QoS diversification for delay-constrained applications.

In the next section, the proposed scheduling policy is described, and a proposal for a low complexity implementation is presented in section 3. In section 4, a queueing model is formulated and the derivation of cell loss (deadline-violation) probabilities and cell delay distributions is presented; detailes of the analysis can be found in are presented in [9]. Finally, some numerical results are presented and discussed in section 5.

## 2 Description of the Scheduling Policy

Consider two different classes of traffic (or applications) sharing a transmission link. The link is slotted and capable of serving one information unit (cell) per time slot. Let $H$ (for high priority) and $L$ (for low priority) denote the two classes; let superscript $H(L)$ denote a quantity associated with class $H(L)$.

(a) H-cells (that is cells of application H) are served according to the Head-of-Line (HoL) priority policy. That is, no service is provided to L-cells unless no H-cell is present. H-cells which experience a delay of more than $T^H$ slots are discarded.

(b) L-cells (that is cells of application L) are served according to the D-HoL priority. That is, L-cells are served according to the HoL priority policy only after they have waited for $D$ time slots. After a waiting time of $D$ slots, L-cells may be viewed as joining the H-cells as fresh arrivals occuring at that time. Since the service policy is work-conserving, L-cells may be served before they switch priority when no H-cells (or switched L-cells) are present. L-cells which experience a delay of more than $T^L$ slots are discarded. In order for the policy to be non-trivial (that is, class switching to be possible), it is assumed that $T^L \geq D$.

(c) Within each class, cells are served according to the First-Come-First-Served (FCFS) policy.

Although the priority jumping in the above scheduling policy resembles this aspect of the HoL-PJ policy proposed in [5], the proposed policy as well as the objectives here are quite different from those in [5]. First, the proposed policy discards cells which miss their deadlines, unlike in [5]. Related to this is the fact that the proposed policy reduces to the STE policy (for $D = T^L - T^H$), while the policy in [5] reduces to the EDD policy under proper parameter setting. Second, the induced cell loss (deadline violation probabilities) are derived in this work as opposed to bounds on the average waiting time in [5]. Finally, while the focus in [5] has been to present a policy which implements the EDD without the processing delay and complexity of time-stamp-based sorting, the objective in this paper is to develop a policy capable of delivering diversified QoS - without wasting capacity to serve expired cells - and an approach to calculate the performance measure of interest.

Since the STE policy has been shown to minimize the total cell loss (deadline violation) probability [7, 8], it is expected that the proposed policy will induce higher total cell loss probability for $D \neq T^L - T^H$. Minimizing the total cell loss probability is not necessarily the most desirable quality of a policy. For instance, it is easy to show that unless the STE policy is non-work-conserving[1], it will induce higher cell loss probability to the class with the smaller deadline. Thus, if the QoS requirement is defined in terms of a lower cell loss probability for the class of cells with the smallest deadline, then the STE policy cannot achieve the desired balance optimally and will have to operate at a lower traffic load to deliver the QoS to both classes (while providing better than specified service to one class). The proposed policy is shown here to be capable of providing for substantial QoS diversification through the control parameter $D$, and, thus will potentially operate at higher traffic load.

An interesting and potentially useful characteristic of the priority service policy studied here is that it can represent a number of known service policies by setting properly key parameters as indicated below.

(a) If $\{D = 0,\ T^H \to \infty,\ T^L \to \infty\}$, the policy becomes the FCFS policy with infinite buffer capacity.

[1] A non-work-conserving STE policy is defined to be one which does not serve any cell from those with the largest of the two (here) deadlines before they experience a delay $D(= T^L - T^H)$.

(b) If $\{D = 0,\ T^H = T^L\}$, the policy becomes the FCFS policy with buffer capacity equal to $T^H$ (complete buffer sharing).

(c) If $\{D = 0,\ T^H \neq T^L\}$, the policy becomes the Nested Thresholds discarding policy, controlling cell losses due to buffer space limitations (space-priority policy); the buffer capacity in this case is equal to $max\{T^H, T^L\}$.

(d) If $\{D \to \infty,\ T^H \to \infty,\ T^L \to \infty\}$, the policy becomes the HoL priority policy with infinite buffer capacities.

(e) If $\{T^L = T^H + D\}$, the policy becomes the Early-Due-Date (EDD) priority policy with buffer capacity equal to $T^L$, or the Shortest Time to Extinction (STE).

## 3 Implementation

Although the proposed scheduling scheme may be implemented in principle by considering time-stamps associated with each cell arrival, such an approach may not be realistic for a high-speed, low-management-complexity switching system. A simple implementation of the cell class-switching and discarding policy is shown in Fig. 1.

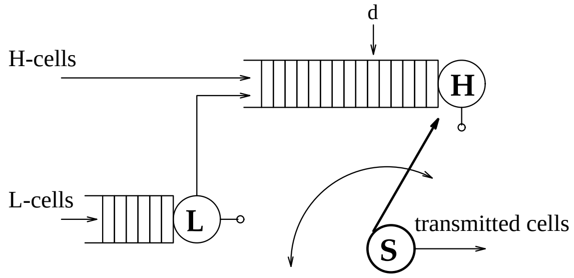


Figure 1: Buffer management with time constraints

As indicated in Fig. 1, H-cells join immediately the H-buffer. If the H-buffer occupacy exceeds a threshold equal to $T^H$, new H-cell arrivals are discarded. Since the H-buffer is served under the HoL priority policy, the discarded H-cells are precisely the ones whose deadline $T^H$ would be violated.

L-cells join the L-buffer which is served only when the H-buffer is empty. Cells in L-buffer which experience a delay $D$ are moved to the end of the queue of H-buffer, provided that the H-buffer occupancy does not exceed $T^L - D$; otherwise, these L-cells are discarded. Again, since the H-buffer is served under the HoL priority policy, the discarded L-cells are precisely the ones whose deadline $T^L$ would be violated.

Notice that the mechanism presented in Fig. 1 implements the (deadline-violating) cell discarding through a simple buffer threshold policy, avoiding a more complex time-stamping approach. The capacity of the H-buffer and L-buffer are equal to $max\{T^H, T^L - D\}$ and $min\{T^L, DN_{max}\}$ respectively; $N_{max}$ is the maximum number of L-cell arrivals per slot. The threshold $d$ in Fig. 1 is equal to $min\{T^H, T^L - D\}$. If $min\{T^H, T^L - D\} = T^H$, then H-cell arrivals which find more than $d$ cells in H-buffer are discarded; otherwise, the latter holds true for L-cells moved to H-buffer.

The identification of the time at which L-cell are moved to H-buffer can be implemented through time-stamping or by adopting the less-complex mechanism described here. Time-stamp based sorting in every slot presents a level of complexity which may not be tolerable in a high-speed networking environment. For this reason, alternative to time-stamp based implementation approaches have been considered in [5] and [8]: a list of cell arrival times and a clock are employed in [5] for each of the $N$ queues considered; one shift register for each of the two classes is employed in [8]. It appears that when multiple arrivals per slot are possible, these implementations can become fairly complex as well. An implementation of the proposed policy utilizes a circular buffer (registers) which records the number of cell arrivals per slot and it is described next.

The L-buffer (Fig. 1) controller is equipped with a pool of $D$ registers, a timer $T$ and a pointer $P$. The timer counts from 0 to $D-1$, increasing its content by one in every slot; after count $D-1$, it is reset at the next slot and then continues as before. The current content of the timer indicates the register in which the number of L-cell arrivals during the current slot will be registered. The pool of registers may be thought of having a circular structure and the timer $T$ may be viewed as a rotating pointer pointing to the register to be used at the current time (Fig. 2). Notice that the register visited by timer $T$ contains the number of L-cells which have experienced a delay $D$ in the L-buffer. These cells - which are at the head of the L-buffer - will be moved to the H-buffer and the number of new L-cell arrivals over the current slot will be registered in this register.

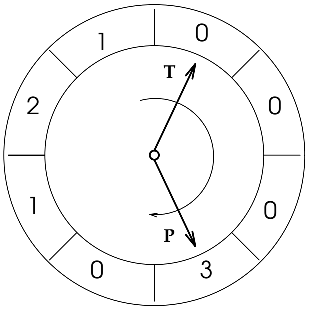


Figure 2: The circular representation of the registers and pointers of the L-buffer controller

The timer $T$ identifies the time when L-cells are moved to the H-buffer. A mechanism is needed to determine changes in the content of the registers due to service provided to L-cells while still in the L-buffer. A pointer $P$ is used for this purpose. This pointer points to the (non-zero-content) register containing the number of L-cells which are the oldest in the L-buffer. When service is provided to the L-buffer - when the H-buffer is empty - the content of the register pointed by pointer $P$ is decreased by one. The pointer $P$ moves from the currently pointed register to the next non-zero-content register if the content of the current register becomes zero. This occurs if the content of the currently pointed register is one and service is provided to an L-cell or if the timer $T$ visits this register and, thus the corresponding L-cells are moved to the H-buffer. If there is currently no L-cell in the L-buffer, $P$ is equal to $T$.

# 4 Performance Analysis

In this section, a numerical approach is developed for the evaluation of the diversified QoS provided to the two classes of traffic. The QoS is defined in terms of the induced cell loss probability; notice that cell loss and cell-deadline violation are identical events under the proposed policy.

## 4.1 System Model

Fig. 3 shows three axes which will be used in the performance analysis of the proposed service policy. The L-axis (H-axis) is used to conveniently describe L-cell (H-cell) arrivals at the time they occur. The system axis is used to conveniently mark the current time. Cell arrival and service completions are assumed to occur at the slot boundaries.

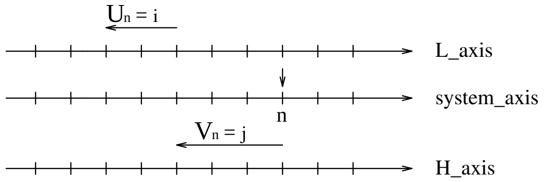


Figure 3: Discrete axes employed in the system study

The H-cell (L-cell) arrival process is assumed to be an independent process and governed by geometrically distributed (per slot) batches with parameter $q^H$ ($q^L$). It should be noted that the assumption on the arrival processes considered above are not to be viewed as critical, since they can be relaxed in a number of ways. For instance, 2-state Markov arrival processes may be considered and the resulting system be analyzed by applying the same approach (requiring increased computations). It is also applicable to arrival processes which are independent and identically (i.i.d.) distributed with arbitrarily distributed batch size; in this case, the maximum batch size affects the magnitude of the numerical complexity.

The analysis approach is based on renewal theory and it is similar to that followed for the study of the systems in [1, 2]. Let $n$, $n \in N$, denote the current time, where $N$ denotes the set of natural numbers; at this time, the server is ready to begin the service of the next cell. Consider the following definitions (see Fig. 3):

$V_n$ : A random variable describing the current length (in slots) of the unexamined interval at H-axis. That is, all H-cell arrivals before time $n - V_n$ have been served; no H-cell arrival after time $n - V_n + 1$ has been considered for service by time $n$.

$U_n$ : A random variable such that $U_n + V_n$ describes the current length of the unexamined interval on L-axis.

It is easy to observe that $\{U_n, V_n\}_{n \in N}$ is a Markov process. Let $\{s_k\}_{k \in N}$ denote a sequence of time instants (slot boundaries) at which the system is empty; $\{s_k\}_{k \in N}$ is a renewal sequence. Consider the following definitions:

$Y_k$ : A random variable describing the length of the $k^{th}$ renewal cycle; $Y$ will denote the generic random variable (associated with a renewal cycle).

$Y_k^H(Y_k^L)$ : A random variable describing the number of H-cells (L-cells) transmitted over the $k^{th}$ renewal cycle; $Y^H(Y^L)$ will denote the generic random variable.

$L_k^H(L_k^L)$ : A random variable describing the number of H-cells (L-cells) lost over the $k^{th}$ renewal cycle; $L^H$ ($L^L$) will denote the generic random variable.

It is easy to establish that

$$Y_k = Y_k^H + Y_k^L + 1 \quad , \quad Y_k \geq 1 \tag{1}$$

Fig. 4 presents a realization of a renewal cycle. Cells marked by $\times$ are the ones which are lost (due to violation of the associated deadline). Transmitted cells are shown on the system axis. In this example, $T^H = 3, T^L = 4, D = 2$. The renewal cycle begins at time $t_0$ at which no cell is present; the first slot of the renewal cycle is always idle (no transmission occurs). At time slot $t_4$, one L-cell is served and the first L-cell is discarded due to the expiration of its deadline ($t_4 - t_1 = T^L$). In fact, at $t_3$ the first two L-cells switch to H-buffer, but only one is served before its deadline. At $t_5$, the L-cells which arrived at $t_3$ switch to H-buffer ($t_5 - t_3 = D$); in this realization, the H-cell which arrived at $t_5$ happens to be served before these L-cells. At $t_9$, the L-cell is served since no H-cell is present. At $t_{10}$, no cell is present and the renewal cycle ends. In this example, $Y_k = 10$, $Y_k^H = 6$, $Y_k^L = 3$, $L_k^H = 1$, $L_k^L = 3$.

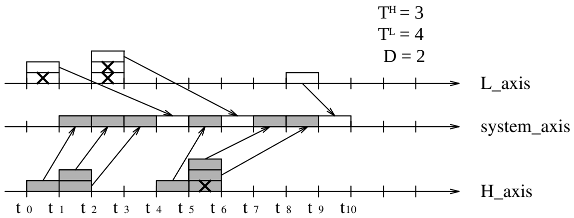


Figure 4: An example of renewal cycle

The evolution of the process $\{U_n, V_n\}$ can be easily derived for the realization shown in Fig. 4. Notice that when $U_n > D$, $U_n$ points to the oldest unexamined slot which is to be served under the HoL priority;

the associated L-cells have switched priority and are the oldest cells in the system. If $U_n < D$, $V_n$ points to the oldest unexamined slot which is to be served under the HoL priority. If $U_n = D$, the oldest unexamined intervals in both axes have the same priority and the selection is made according to a probabilistic rule introduced later; any selection rule can be adopted.

## 4.2 Derivation of System Equations

The following definitions will be used in the analysis:

- $Y^H(i,j)(Y^L(i,j))$ : A random variable describing the number of H-cells (L-cells) transmitted over the interval between a time slot at which $\{U_n, V_n\}$ is in state $(i,j)$ and the end of the renewal cycle which contains this slot.
- $L^H(i,j)(L^L(i,j))$ : A random variable describing the number of H-cells (L-cells) discarded over the interval between a time slot at which $\{U_n, V_n\}$ is in state $(i,j)$ and the end of the renewal cycle which contains this slot.
- $S_{\{i,j\}}$: An indicator function assuming the value one if there is a possibility to discard an L-cell as a result of the service to be provided in the current slot (due to resulting violation of its deadline $T^L$)

$$S_{\{i,j\}} = \begin{cases} 1 & \text{if } i+j = T^L \\ 0 & \text{otherwise} \end{cases}$$

- $I^H(I^L)$ : An indicator function assuming the value 1 if an H-cell (L-cell) is present at the slot of H-axis (L-axis) under current examination (as pointed to by $V_n$ or $U_n + V_n$); it assumes the value 0 otherwise.
- $\hat{I}^H(\hat{I}^L)$ : An indicator function defined as : $\hat{I}^H = 1 - I^H$ $(\hat{I}^L = 1 - I^L)$.
- $[i,j]^*$ : It is a function which determines the next state of $\{U_n, V_n\}$ taking into consideration possible violation of $T^L$:

$$[i,j]^* = \begin{cases} (i,j) & i+j \le T^L \\ (T^L - j, j) & \text{otherwise} \end{cases}$$

- $m$ : It denotes the lowest possible value of random variable $V_n$; $m = 0$ if $D \neq 0$ and $m = -1$ if $D = 0$.
- $I_{\{H\}}$ $(I_{\{L\}})$ : An indicator function associated with decisions regarding the slot to be examined next when $U_n = D$. $I_{\{H\}} = 1 (I_{\{L\}} = 1)$ if the oldest unexamined slot in H-axis (L-axis) is considered next, and $I_{\{H\}} = 0$ $(I_{\{L\}} = 0)$ otherwise. This is a design parameter which can impact on the induced cell losses. The expected values of these functions ($\mu^H = P\{I_{\{H\}} = 1\}$, $\mu^L = P\{I_{\{L\}} = 1\}$) are derived in [9] under the assumption that all cells (from both classes) arrived over the slots to be examined when $U_n = D$ are equally likely to be selected.
- $\bar{X}$ : Denotes $E\{X\}$, where $E\{\cdot\}$ is the expectation operator.

In the sequel, recursive equations are derived for the calculation of $\bar{L}^H$ and $\bar{L}^L$.

It is easy to observe that no cell is transmitted in the first slot, and, thus, process $\{U_n, V_n\}$ actually starts from state $(0,1)$. Thus,

$$L^H = L^H(0,1) \quad , \quad L^L = L^L(0,1) \tag{2}$$

A careful consideration of the evolution of the recursions presented below shows that when process $\{U_n, V_n\}$ reaches the state $(0,0)$, the renewal cycle ends. For this reason,

$$L^H(0,0) = 0 \quad , \quad L^L(0,0) = 0 \tag{3}$$

to terminate the current cycle. Notice also that $U_n$ can exceed $D+1$ only if $V_n = T^H$. Two cases need to be considered: $T^L \ge T^H$ and $T^L < T^H$.

<u>Case *A*</u> : $T^L \ge T^H$

<u>Case A.1</u> : $T^H > j > 0$, $min(T^L - j, D+1) \ge i \ge m$

(1) $i < D$

$$\begin{aligned} L^H(i,j) &= L^H([i + \hat{I}^H, j - 2\hat{I}^H + 1]^*) \ , \\ L^L(i,j) &= I^H S_{\{i,j\}} N^L + L^L([i + \hat{I}^H, \\ & \quad j - 2\hat{I}^H + 1]^*) \end{aligned} \tag{4}$$

(2) $i = D+1$

$$\begin{aligned} L^H(D+1,j) &= L^H([i - \hat{I}^L, j - \hat{I}^L + 1]^*) \ , \\ L^L(D+1,j) &= I^L S_{\{D+1,j\}} N^L + L^L([i - \hat{I}^L, \\ & \quad j - \hat{I}^L + 1]^*) \end{aligned} \tag{5}$$

(3) $i = D$

$$\begin{aligned} L^H(D,j) &= L^H([i + \hat{I}^H, j - 2\hat{I}^H + 1]^*) I_{\{H\}} \\ & \quad + L^H([i - \hat{I}^L, j - \hat{I}^L + 1]^*) I_{\{L\}} \ , \\ L^L(D,j) &= \{I^H S_{\{D,j\}} N^L + L^L([i + \hat{I}^H, \\ & \quad j - 2\hat{I}^H + 1]^*)\} I_{\{H\}} \\ & \quad + \{I^L S_{\{D,j\}} N^L + L^L([i - \hat{I}^L, \\ & \quad j - \hat{I}^L + 1]^*)\} I_{\{L\}} \end{aligned} \tag{6}$$

<u>Case A.2</u> : $j = T^H$, $T^L - T^H \ge i \ge m$

<u>(1) $i < D$</u>

$$L^H(i,T^H) = I^H N^H + L^H([i+1, T^H - \hat{I}^H]^*) \quad ,$$
$$L^L(i,T^H) = I^H S_{\{i,T^H\}} N^L + L^L([i+1, T^H - \hat{I}^H]^*) \quad (7)$$

(2) $i \geq D+1$

$$L^H(i,T^H) = I^L N^H + L^H([i - 2\hat{I}^L + 1, T^H]^*) \quad ,$$
$$L^L(i,T^H) = I^L S_{\{i,T^H\}} N^L + L^L([i - 2\hat{I}^L + 1, T^H]^*) \quad (8)$$

(3) $i = D$

$$L^H(D,T^H) = \{I^H N^H + L^H([i+1, T^H - \hat{I}^H]^*)\} I_{\{H\}} + \{I^L N^H + L^H([i - 2\hat{I}^L + 1, T^H]^*)\} I_{\{L\}} \quad ,$$
$$L^L(D,T^H) = \{I^H S_{\{D,T^H\}} N^L + L^L([i+1, T^H - \hat{I}_H]^*)\} I_{\{H\}} + \{I^L S_{\{D,T^H\}} N^L + L^L([i - 2\hat{I}^L + 1, T^H]^*)\} I_{\{L\}} \quad (9)$$

Case A.3 : $j = 0, \quad min(T^L, D+1) \geq i \geq 1$

$$L^H(i,0) = L^H([i - \hat{I}^L, 1 - \hat{I}^L]^*) \quad ,$$
$$L^L(i,0) = I^L S_{\{i,0\}} N^L + L^L([i - \hat{I}^L, 1 - \hat{I}^L]^*) \quad (10)$$

Case B : $T^L < T^H$

The equations under this case are derived similarly; details can be found in [9]. By applying the expectation operator to the above equations, the following systems of linear equations are obtained; details may be found in [9].

$$\bar{L}^H(i,j) = a'^H(i,j) + \sum_{(i',j') \in R_0} b^H(i,j,i',j') \bar{L}^H(i',j')$$
$$\bar{L}^L(i,j) = a'^L(i,j) + \sum_{(i',j') \in R_0} b^L(i,j,i',j') \bar{L}^H(i',j')$$

where $R_0 = \{(i,j) : m \leq i \leq T^L \ , \ 0 \leq j \leq T^H\}$. It should be noted that these systems of linear equations are extremely sparse: only two to four coefficients are not zero per equation. Thus, it can be solved efficiently by using an iterative approach. The computation complexity is of the order of $DT^H$. From the solution of these equations, $\bar{L}^H$ and $\bar{L}^L$ are obtained from (see (2))

$$\bar{L}^H = \bar{L}^H(0,1) \quad , \quad \bar{L}^L = \bar{L}^L(0,1) \quad (11)$$

Similar equations are derived for the calculation of $\bar{Y}^H$ and $\bar{Y}^L$ (refer to [9]). The cell loss probabilities $P^H_{loss}$ for H-cells and $P^L_{loss}$ for L-cells are obtained from the following expressions

$$P^H_{loss} = \frac{\bar{L}^H}{\bar{Y}^H + \bar{L}^H} \quad ,$$
$$P^L_{loss} = \frac{\bar{L}^L}{\bar{Y}^L + \bar{L}^L} \quad (12)$$

Finally, the similar approach for the calculation of the average cell delay and cell delay tail probabilities can be found at [9].

## 5 Numerical Result

Results for the L-cell and H-cell loss probabilities ($P^L_{loss}$ and $P^H_{loss}$, respectively) as functions of $D$ are shown in Fig. 5 and Fig. 6, respectively, under the parameters: $\lambda^H = \lambda^L$ and $\lambda^H + \lambda^L = 0.9, 0.86, 0.82$; $T^H = 50$ and $T^L = 100$. The expected monotonic increase (decrease) of $P^L_{loss}$ ($P^H_{loss}$) as $D$ increases is clearly observed. $P^H_{loss}$ is minimized for $D = 100$, which corresponds to the HoL priority service policy for the H-class. The FCFS policy with different cell admission thresholds ($T^H$ and $T^L$) is determined for $D = 0$: all cells are admitted under buffer occupancy less than 50 ($= T^H$); only L-cells are admitted under buffer occupancy greater than 50; no cell is admitted under buffer occupancy greater than 100 ($= T^L$). Due to the difference in deadlines (or admission thresholds) this policy induces unequal cell loss probabilities ($10^{-5}$ for H-cells and $10^{-23}$ for L-cells, for $\lambda = 0.86$). Practically, the application with the largest deadline suffers almost no losses while the induced losses for the other application may be unacceptably high. Finally, the Shortest Time to Extinction (STE) policy is determined for $D = T^L - T^H = 50$. It is clear from the results shown in Fig. 5 and Fig. 6 that the parameter $D$ can provide for enormous diversification of the induced cell losses. For the deadlines and rates considered in Fig. 5 and Fig. 6 the range of achieved values for $P^H_{loss}$ and $P^L_{loss}$is more than 15 orders of magnitude.

To illustrate the efficiency and flexibility of the proposed policy, consider two applications with deadlines as in Fig. 5 and Fig. 6. Let the QoS be defined by a cell loss requirement given by $\{P^H_{loss} < 10^{-10} \ , \ P^L_{loss} < 10^{-5}\}$. Fig. 5 and 6 indicate that none of the "standard" policies - determined by $D = 50 = T^L - T^H$ (STE), $D = 0$ (FCFS) or $D = 100 = T^L$ (HoL) - can deliver this QoS under total load equal to 0.90. For $D = 63$, the proposed policy can deliver this QoS at a load equal to 0.90. This example illustrates that the STE policy can be sub-optimal with respect to the achieved resourse utilization.

Although the discrete-valued range of $D$ could create a granularity problem regarding the achievable values for $P^H_{loss}$ and $P^L_{loss}$, this is not the case due to the additional fine-tuning provided by the class selection probabilities $\mu^H$ and $\mu^L$. While in this work $\mu^H$ and $\mu^L$ have been selected to correspond to a random selection of the cell to be served next among all qualified cells, it is evident that these probabilities can be set arbitrarily (under the constraint $\mu^H + \mu^L = 1$) to bias accordingly the induced values of $P^H_{loss}$ and $P^L_{loss}$.

Let $P^H_{k,x}$ denote the induced value of $P^H_{loss}$ for $D = k$ and $\mu^H = x$, $0 \leq k \leq T^L$, $0 \leq x \leq 1$. Fig. 7 presents some results for $P^H_{14,x}$ versus $x = \mu^H$, $0 \leq x \leq 1$; $\lambda^H = \lambda^L = 0.45$, $T^H = 6$ and $T^L = 20$. The results illustrate the continuity of the achieved range of cell loss probabilities. It was also found that $P^H_{14,1} = P^H_{15,0}$ and $P_{13,1} = P^H_{14,0}$ as a carefull consideration of the policy under such parameters would suggest. Results are shown for the L-cell loss probability for $D = 14$ and $\mu^H = x$ - denoted by $P^L_{14,x}$ - as well. Finally, by comparing the results in Fig. 5 and Fig. 6 and those in Fig. 7, it may be concluded that the parameter $D$ can provide for a much greater QoS diversification compared to that achieved through parameter $\mu^H$.

Fig. 8 and 9 present results for $P^L_{loss}$ and $P^H_{loss}$, respectively, as a function of $D$ for $0 \leq D \leq T^H = 80$ and for various values of $T^L$ (70, 75 and 80); $\lambda^H = \lambda^L = 0.45$. These results can provide for a comparative study of the effectiveness of the proposed policy and the Nested Thresholds discarding policy identified for $D = 0$ and $T^H \neq T^L$. Assuming the above parameters and a buffer capacity equal to $T^H$, QoS diversification under the Nested Thresholds policy can be achieved by varying the threshold $T^L$. Under this policy $P^L_{loss} < 10^{-5}$ can be achieved for $T^L \geq 70$, indicating a minimum value of $P^H_{loss}$ greater than $10^{-9}$. Under the proposed policy $P^L_{loss} < 10^{-5}$ can be achieved under, for instance, $T^L = 80$ and $D = 20$, indicating a value of $P^H_{loss}$ of about $10^{-12}$.

Finally, Fig. 10 and 11 present a comparison between the induced deadline violation probabilities under the proposed policy (which does not serve expired cells) and an otherwise identical policy which serves all cells; $\lambda^H = \lambda^L = 50$. The deadline violation probability under the latter policy is equal to the tail of the delay distribution beyond the value 50 of a system operating under the proposed policy with $T^H = T^L = \infty$. Since the latter system is of infinite dimensionality, a truncated system at $T^H = T^L = 120$ is solved providing a very tight lower bound to the tail of the infinite dimensional system. The results clearly indicate the benefit obtained by not serving expired cells if deadline-violation probability is to be minimized.

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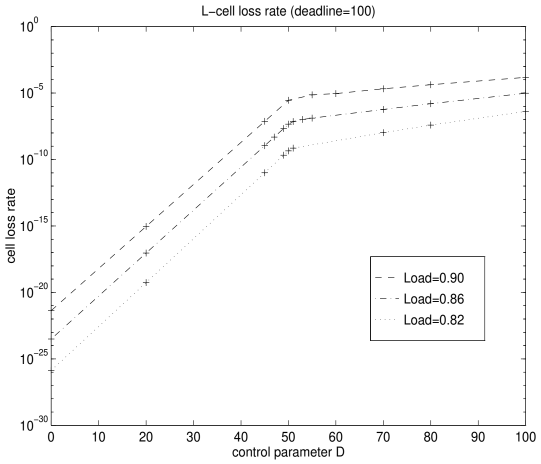


Figure 5: L-cell loss probability versus $D$ under different loads

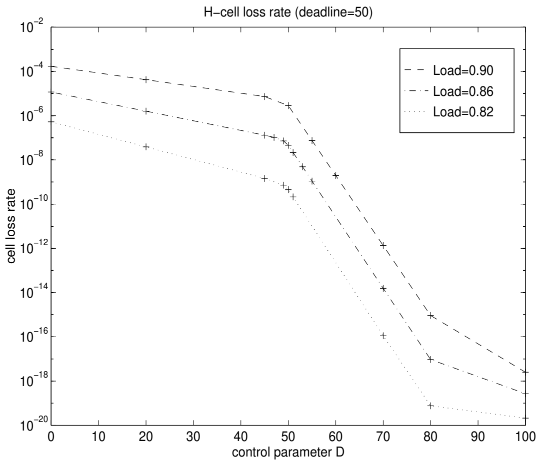


Figure 6: H-cell loss probability versus $D$ under different loads

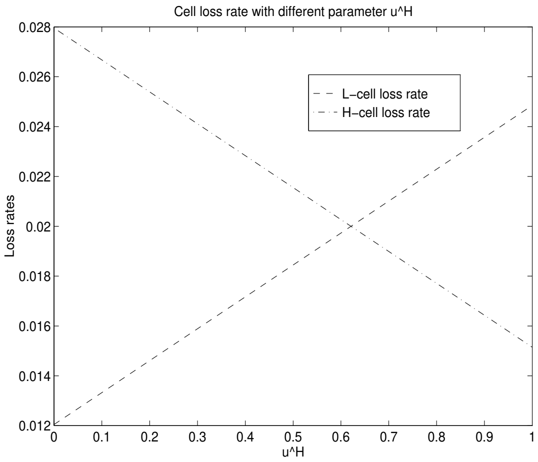


Figure 7: Cell loss rates versus $\mu^H$

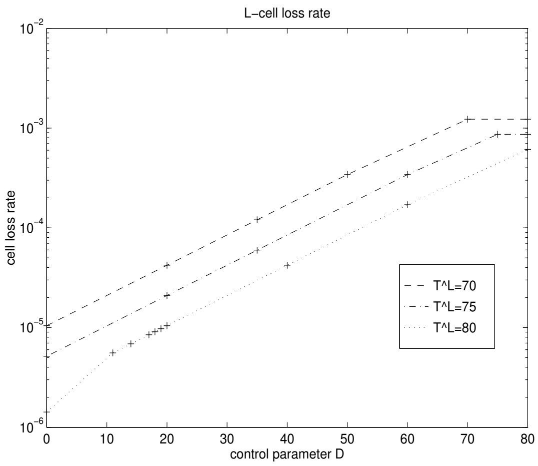


Figure 8: L-cell loss probability versus $D$ under different L-cell deadlines

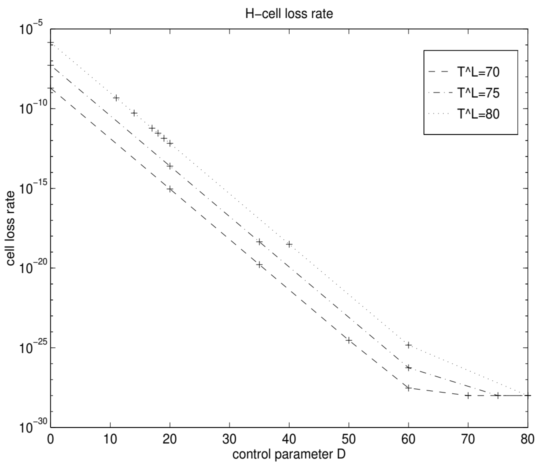


Figure 9: H-cell loss probability versus $D$ under different L-cell deadlines

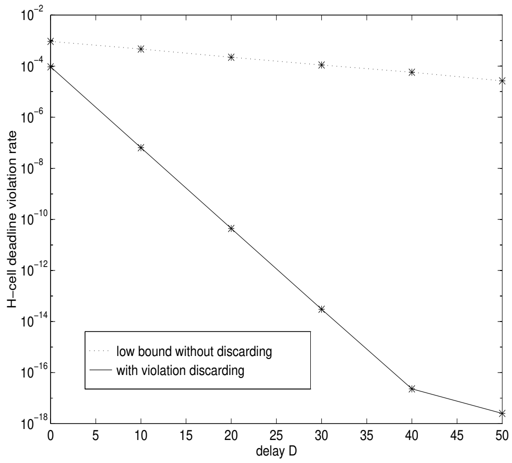


Figure 10: H-cell deadline violation with and without discarding

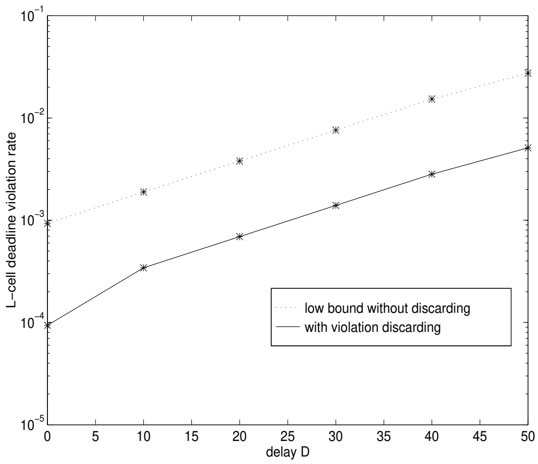


Figure 11: L-cell deadline violation with and without discarding