Multi-Level Threshold for Priority Buffer Space Management in ATM Networks

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Abstract— This paper addresses a multi-level threshold strategy for buffer space management in ATM networks. We consider a buffer of finite capacity loaded with a number of On-Off sources. Each source generates two types of cells, high priority cells and low priority cells. An arriving cell of low priority will be rejected if the buffer content at the cell arrival epoch exceeds a specified threshold. Instead of using a unique threshold level, in this paper, we introduce a multi-level threshold strategy where each level is assigned to a maximum admissible cell arrival rate. Once the buffer content is over a threshold level and the cell arrival rate is found higher than the corresponding admissible rate, all incoming cells of low priority are discarded. This strategy, through properly adjusting the admissible arrival rate under a given threshold, can efficiently balance the overall load of the buffer. Numerical study illustrates that our multi-level threshold strategy is superior to the fixed threshold in buffer space management.

I. Introduction

ATM based broadband ISDN is of capability to support diverse classes of traffic such as voice, video and data etc.. To maintain good performance of the network so as to guarantee the quality requirements of each class of traffic [8], a number of control mechanisms have to be employed. One scheme is referred to as *Space Priority*, where each traffic source merged in a multiplexor or each cell belonging to a same traffic source may be assigned different in priority at the connection level or cell level of the network, respectively [6]. Under proposed ATM standards, one bite is reserved in the head of an ATM cell to identify the priorities [5].

To implement a space priority scheme, two mechanisms have been proposed, namely, *Push-out mechanism* and *Partial buffer sharing*. The former permits incoming cells of high priority to overwrite the existent cells of low priority if congestion occurs, resulting in loss of low priority cells. The latter mechanism, however, applies a threshold to low priority cells. Whenever buffer content exceeds the threshold, arriving cells of low priority will be discarded. Comparative studies reveal that the partial buffer sharing is less efficient than push-out mechanism in buffer space controls, but it is much easy to implement [6].[11]. This conclusion has also been confirmed by simulation studies [1].

Stochastic fluid model is first introduced by Anick *et al.* in [2], where multiple On-Off sources are offered to multiplex in a finite capacity buffer, and cell length is assumed fixed. The model was later extended to evaluate the performance of loss priority system by Elwalid *et al.* [3], where all cells are ranked in two or even more priority scales. To handle high dimensional source models, an algebraic theory is developed for efficient computation of matrix operations. The fluid flow model is also used in [12], which examines the performance of both source threshold and buffer threshold. As a result, the relationship between cell waiting time and the threshold level is revealed. This is very useful to determine maximum threshold level subject to maximum tolerable packet delay. As a simple case, a single On-Off source is considered [7], and the optimal threshold is derived to ensure the minimum bandwidth requirement subject to the loss probability constraints of two streams with different priority.

The threshold, once chosen, will retain a fixed level. The effect of dynamically varying the threshold on the buffer management is still unknown. In this paper, our attention is focused on an investigation of multi-level threshold in ATM buffer management. We consider a buffer loaded with multiple On-Off sources, and assume all cells are classified into high priority cells and low priority cells, namely, priority cells and tagged cells correspondingly. If the buffer content exceeds a designed threshold level, tagged cells may be discarded depending on the cell arrival rate. Due to burstiness of On-Off traffic, cell arrival rate fluctuates dynamically. Our multi-level threshold strategy enables the threshold levels to adapt to the variations of arrival rate. Eventually, it can balance the overall load of the buffer, and improve the performance of both types of cells.

The remainder of the paper is organized as follows. In section II, a stochastic fluid model is presented. The model plays a key role in the analysis of buffer performance. Section III concentrates on the introduction and performance evaluation of the multi-level threshold strategy. Numerical example and final conclusions are shown in section IV and V, respectively.

II. Fluid Flow Model

In this section, we describe the assumptions we make about the system to be modeled and the characteristics of On-Off sources, as well as the fluid flow model.

A. Traffic Model Assumptions

1. N identical and independent sources are multiplexed, each source is characterized by a On-Off model. The state On and

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Off present *active* and *silent* duration, respectively. Two states appear alternatively, both On and Off periods are distributed exponentially with means $1/\beta$ and $1/\alpha$, respectively.

2. All cells are classified into two types, priority cells and tagged cells, in terms of loss priority. An active source will generate both priority and tagged cells simultaneously with rates λ_p and λ_t, respectively. No cell is produced if silent.

With the N sources, the superposed traffic can be modeled by a N+1-state Markov chain.Let V be the number of active sources, where $V \in \mathcal{N}$ and $\mathcal{N} = \{0, 1, 2, \cdots N\}$. Given $V = v$, the arrival rate of priority cells turns to be $\nu\lambda_p$, and that of tagged cells $v\lambda_t$. The steady solution to the process is simply formulated as

$$G_v = \binom{N}{v} \left(\frac{\alpha}{\alpha+\beta}\right)^v \left(\frac{\beta}{\alpha+\beta}\right)^{N-v}, \quad \text{for } v \in \mathcal{N}$$

where G_v is the state probability that $V = v$.

B. System Assumptions

We consider an ATM multiplexor buffer, thereby making the following assumptions.

1. The buffer capacity is M, and a group of threshold levels apply to tagged cells. Priority cells will be discarded only when the buffer is full. Tagged cells are dropped if the buffer content exceeds the threshold corresponding to their arrival rate. This scheme belongs to a partial buffer sharing management strategy, and the loss probability for priority cell can be guaranteed via properly setting threshold levels.

2. Cell service rate is assumed deterministic as μ. Correspondingly, the mean transmission time of a cell is equal to $1/\mu$.

C. Stochastic Fluid Model

Define a stochastic variable Z to be the buffer content at time t, there is $0 \leq Z \leq M$. A fluid flow model is governed by [4]

$$\frac{dZ}{dt} = \rho^{in} - \rho^{out} \tag{2.1}$$

where ρ^{in} denotes total cell arrival rate, and ρ^{out} departure rate.

In the problem we are concerning, the total arrival rate basically varies with the number of active sources V, but also depends on buffer content Z as well. This is because discarding tagged cells gives rise to a decrease of arrival rate. e.g. whenever the buffer content grows above a threshold level, cell arrivals could be contributed by priority cells along. Therefore, given $V = v$, equation (2.1) can be rewritten to

$$\frac{dZ}{dt} = \begin{cases} v(\lambda_p + \lambda_t) - \mu & \text{If tagged cells are permitted} \\ v\lambda_p - \mu & \text{If tagged cells are rejected} \end{cases}$$

Consider both Z and V, a bivariate Markov process (V, Z) is formed. Let $\Gamma_v(z)$ be the steady state probability distribution, which is defined as

$$\Gamma_v(z) = Pr\{V = v, Z \leq z\}$$

where $v \in \mathcal{N}$ and $0 \leq z \leq M$. $\Gamma_v(z)$ can be obtained by solving following differential equation[3],

$$\frac{d\Gamma(z)}{dz} = A\Gamma(z) \tag{2.2}$$

where $\Gamma(z) = [\Gamma_0(z), \Gamma_1(z), \cdots \Gamma_N(z)]^T$, and $A = R^{-1}W$. R is diagonal matrix, its vth diagonal element, ρ_v or $\tilde{\rho}_v$, is the change rate of buffer content when tagged cells are permitted or discarded, respectively.

$$\rho_v = v(\lambda_p + \lambda_t) - \mu, \quad \tilde{\rho}_v = v\lambda_p - \mu \tag{2.3}$$

While matrix W is just the transpose of the finitesimal generator of a birth-death process which represents the V process.

$$W_{ij} = \begin{cases} (N-i)\alpha & j = i-1 \\ -[(N-i)\alpha + i\beta] & j = i \\ i\beta & j = i+1 \end{cases}$$

The solution to equation (2.2) is of the form

$$\Gamma(z) = e^{Az}c \ (0 \leq z \leq M) \tag{2.4}$$

the coefficient c can be determined by its boundary conditions[3].

Previous studies have been mainly restricted to fixed threshold, tagged cells will absolutely be discarded as long as buffer content exceeds the threshold level. We argue that, since cell arrival rate varies with the number of active sources, load-dependent multiple thresholds may lead to better performance in buffer space management.

III. Multi-Level Threshold

In this section, the multi-level threshold strategy is investigated, including traffic load definition, buffer space description, and buffer performance evaluation.

A. Overview of Traffic Load

As mentioned in the preceding section, the threshold is updated according to cell arrival rate. The arrival rate depends on the number of active sources V and whether or not tagged cells have been discarded. If we take a look at the change trend of buffer content which is governed by the relation (2.3), V falls to the following three states.

Underload $\mathcal{N}_u$, where

$$\mathcal{N}_u = \{v : \rho_v \leq 0, \tilde{\rho}_v \leq 0, v \in \mathcal{N}\}$$

This implies that, if $V \in \mathcal{N}_u$, buffer content tends to drop down continuously even when tagged cells are permitted to enter the buffer.

Overload $\mathcal{N}_o$, where

$$\mathcal{N}_o = \{v : \rho_v > 0, \tilde{\rho}_v > 0, v \in \mathcal{N}\}$$

This means that, as $V \in \mathcal{N}_o$, buffer content turns to grow up even after tagged cells have been discarded, so cell loss possibly occurs.

Controllable $\mathcal{N}_c$, where

$$\mathcal{N}_c = \{v : \rho_v > 0, \tilde{\rho}_v \leq 0, v \in \mathcal{N}\}$$

Once V varies in this state, dropping tagged cells will protect the buffer from continuous growth in content, loss of priority cells can therefore be avoided. This is just what we expect from a partial buffer sharing scheme.

B. Multi-Level Threshold

It is ideal to let the traffic load fluctuate in the controllable state, because under this load, priority cell discarding strategy works efficiently. Under other states, such as underload for instance, a higher cell rate can be accepted; but a lower rate is expected when under overload. Heuristically, the threshold levels should adapt to the traffic load, or the number of active sources V as shown in Fig 1. The threshold levels L_u, L_c and L_o apply to traffic Underload, Controllable and Overload states, respectively. Each level specifies a maximum admissible cell arrival rate, this will be explained later.

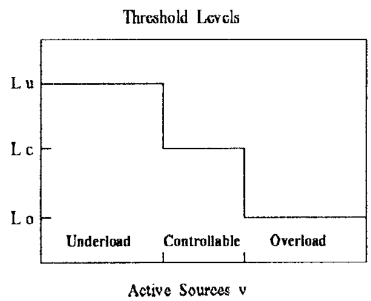

Figure 1: Ideal threshold levels

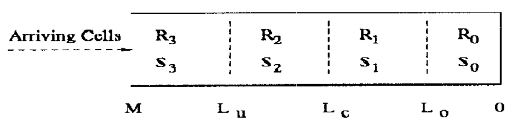

Figure 2: Buffer spaces indication

As multi-level threshold is introduced, the buffer spaces are accordingly divided into four sections, $\mathcal{S}_0$, $\mathcal{S}_1$, $\mathcal{S}_2$ and $\mathcal{S}_3$, which represent buffer level from 0 to L_o, from L_o to L_c, from L_c to L_u and from L_u to M, respectively, see Fig 2.

The draft rate matrix R of equation (2.2) in each buffer space section can be given as follows

• $\mathbf{Z} \in \mathcal{S}_0$. As no cell is dropped under this buffer state, both priority and tagged streams are permitted to enter the buffer.

$$R_0 = \text{diag}\{\rho_0, \rho_1, \cdots, \rho_v, \cdots, \rho_N\}, \quad v \in \mathcal{N}$$

• $\mathbf{Z} \in \mathcal{S}_1$. Threshold L_o applies, but tagged cells are dropped only if the traffic load is in overload state, i.e. $v \in \mathcal{N}_o$.

$$R_1 = \text{diag}\{r_1^1, r_1^2\}$$

where

$$r_1^1 = \text{diag}\{\rho_0, \rho_1, \cdots, \rho_v, \cdots, \rho_{N_1}\}, N_1 = \max\{v : v \in \mathcal{N}_u \cup \mathcal{N}_c\}$$

and

$$r_1^2 = \text{diag}\{\tilde{\rho}_{N_1+1}, \cdots, \tilde{\rho}_i, \cdots, \tilde{\rho}_N\}, \quad i \in \mathcal{N}_o$$

$N_1\lambda_t$ is referred to as the maximum admissible tagged cell arrival rate against threshold L_o.

• $\mathbf{Z} \in \mathcal{S}_2$. Threshold L_c applies to the tagged cells whose traffic load grows up to overload or controllable states. So the draft rate is formed by,

$$R_2 = \text{diag}\{r_2^1, r_2^2\}$$

where

$$r_2^1 = \text{diag}\{\rho_0, \rho_1, \cdots, \rho_v, \cdots, \rho_{N_2}\}, N_2 = \max\{v : v \in \mathcal{N}_u\}$$

and

$$r_2^2 = \text{diag}\{\tilde{\rho}_{N_2+1}, \cdots, \tilde{\rho}_i, \cdots, \tilde{\rho}_N\}, \quad i \in \mathcal{N}_c \cup \mathcal{N}_o$$

To the threshold L_c, the maximum admissible rate becomes $N_2\lambda_t$.

• $\mathbf{Z} \in \mathcal{S}_3$. Threshold L_u applies to all tagged cells. Once buffer content is above this level, all tagged cells are rejected, therefore,

$$R_3 = \text{diag}\{\tilde{\rho}_0, \cdots, \tilde{\rho}_i, \cdots, \tilde{\rho}_N\}, \quad i \in \mathcal{N}$$

We can conclude from above analysis that a decision whether to accept or to reject a tagged cell is made based on the information of current buffer content level and cell arrival rate as well. If cell arrival rate exceeds $N_1\lambda_t$, for example, the traffic load goes up to overload state, incoming tagged cells will be discarded as long as the buffer content exceeds the threshold L_o. In brief, a high arrival rate corresponds to a low threshold level, and vice versa. Or in terms of threshold, a low threshold level tolerates to a high maximum admissible rate, and vice versa. For example, if the buffer content is above L_o but below L_c, the maximum admissible rate of tagged cells can be as high as $N_1\lambda_t$. While if the buffer content is above L_c but below L_u, the maximum admissible rate drops to $N_2\lambda_t$. In conclusion, at any circumstances, tagged cells with higher arrival rate than the defined admissible rate will be certainly discarded.

Given draft rate in each buffer section, probability distribution $\Gamma(z)$ can be expressed by

$$\Gamma^i(z) = e^{A_i z} c_i \quad i \in \{0, 1, 2, 3\}$$

where $A_i = R_i^{-1} W$, which is a coefficient matrix corresponding the section concerned. Initial constant c_i needs to be determined with the help of some boundary conditions [9].

C. Loss Probability Evaluation

According to the buffer management assumptions, priority cells will be lost only if the buffer is full. From the definition of quantity $\Gamma_v(z)$, it can be seen that, for given traffic load v, the probability that the buffer is full is obtained by

$$P_{full} = G_v - \Gamma_v^3(M) \quad v \in \mathcal{N}$$

Therefore, the cell loss rate is calculated by

$$r_{loss} = \sum_{v=0}^{N} (v\lambda_p - \mu)[G_v - \Gamma_v^3(M)]$$

Then the loss probability of priority cells can easily be formulated as

$$P_{loss}^p = \frac{r_{loss}}{\sum_{v=0}^{N} v\lambda_p G_v} \tag{3.1}$$

where the denominator denotes the mean arrival rate of priority cells.

Working out the loss probability for a tagged cell is a little bit more difficult than for a priority cell. For tagged cells, cell loss can be caused by either discarding or buffer congestion. Accordingly, As the multi-level threshold is considered, loss rate has to be investigated individually in each traffic load state.

• $V \in \mathcal{N}_u$. Under this load, tagged cells are discarded only if the buffer content exceeds the level L_u. Therefore, the corresponding loss rate will be evaluated by,

$$r_{loss} = \sum_{v \in \mathcal{N}_u} v\lambda_t [G_v - \Gamma_v^3(L_u)]$$

• $V \in \mathcal{N}_c$. Threshold level L_c applies to this load, cell discarding rate will be

$$r_{loss} = \sum_{v \in \mathcal{N}_c} v\lambda_t [G_v - \Gamma_v^2(L_c)]$$

But as it is indicated [9] that there is a step change over the conditional probability distribution of buffer content. The change just represents the conditional probability of buffer content at level L_c. At this level, the buffer will reject those extra tagged cells, leading to loss of tagged cells at rate,

$$r_c = [v(\lambda_p + \lambda_t) - \mu](\Gamma_v^2(L_c) - \Gamma_v^1(L_c))$$

where $\Gamma_v^2(L_c) - \Gamma_v^1(L_c)$ gives the probability that buffer content is equal to L_c.

• $V \in \mathcal{N}_o$. The corresponding threshold is L_o, the loss rate turns to be

$$r_{loss} = \sum_{v \in \mathcal{N}_o} v\lambda_t [G_v - \Gamma_v^1(L_o)]$$

Based on above analysis, the total loss probability for tagged cells will be the sum of all the loss rate obtained, divided by mean cell arrival rate known as $\sum_{v \in \mathcal{N}} v\lambda_t G_v$.

IV. Numerical Example

Due to the fact that we can't obtain an analytical solution for quantity $\Gamma(z)$, the performance of our multi-level threshold can only be verified by some sort of numerical evaluation or computer simulation. Due to limited scope of this paper, only numerical analysis is given in this section.

The parameter used here are chosen arbitrarily. Suppose both priority and tagged streams are of the same characteristics. Let $\alpha = 0.4$, $\beta = 1$ and $N = 12$, and cell arrival rate $\lambda_p = 1.0$ and $\lambda_t = 0.8$. The buffer capacity M is assumed equal to 10. Cell transmission rate μ is fixed as 9.79. Under these assumptions, we have $\mathcal{N}_u = \{0, 1, 2, 3, 4, 5\}$, $\mathcal{N}_c = \{6, 7, 8, 9, \}$ and $\mathcal{N}_o = \{10, 11, 12\}$, and $N_1 = 9$, $N_2 = 5$.

Fig 3 illustrates the loss probabilities of priority cells and tagged cells against total number of sources, under two different control schemes: fixed threshold and multi-level threshold. One can clearly see from the graph (a) that the loss probability of priority cells is considerably reduced by using multi-level threshold. This finding can be easily explained.

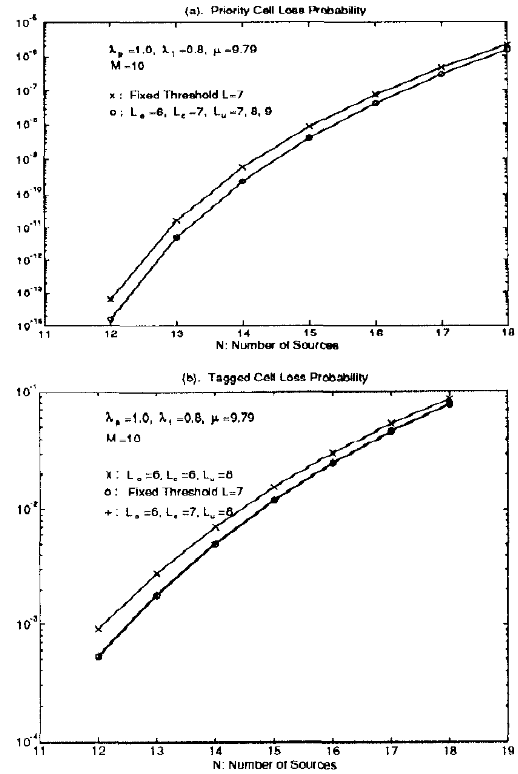

Figure 3: Cell loss probability

Since we have largely got rid of tagged cells through adjusting the threshold to a low level when cell arrival rate is high, more spaces are resultantly reserved to priority cells, and the reduction of cell loss is certainly achieved. The explanation can be found from Fig 4 which shows the decrease of the probability that the buffer is full.

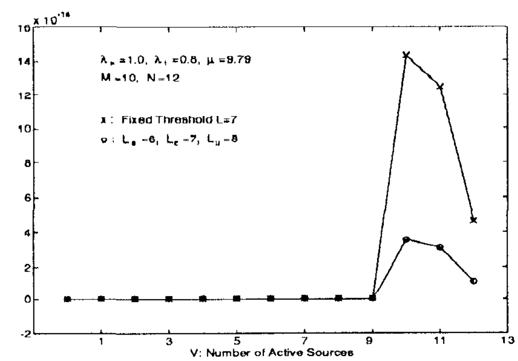

Figure 4: Probability that buffer is full

In addition, it is noticed that varying the threshold L_u affects little on the loss probability of priority cell. This is because cell loss is caused only under overload traffic, i.e. as V above 9 in Fig 4. But the variations of L_u may have indirect impact on priority cell loss.

Fig 3 (b) presents the loss probability of tagged cells. It shows that the increase of loss probability due to applying a lower threshold L_o is minor if a higher threshold level L_u is chosen as a trade-off. The reason can be found from Fig 5 and 6. By using multi-level threshold, the probabilities that the buffer is over the thresholds L_u and L_c are both dropped down. Besides, The probability that the buffer content is at the threshold L_c also falls down. A increase happens only at L_o. Therefore, there is no surprise that the loss probability of tagged cells still possibly remains unchanged.

The level L_c seems very crucial to tagged cells. Lower L_c leads to a remarkable increase in loss probability.

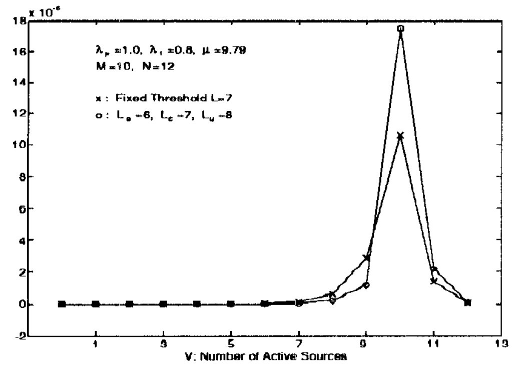

Figure 5: Probability that buffer is over the thresholds

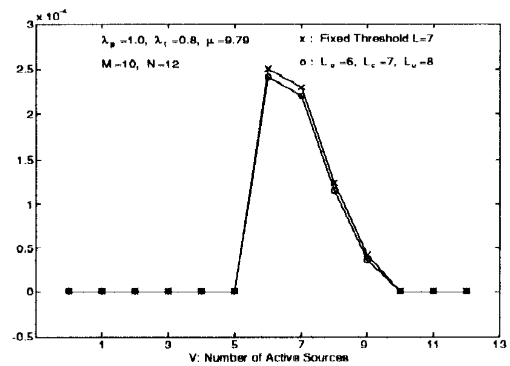

Figure 6: Probability that buffer content is at the thresholds

V. Conclusions

This paper deals with a very popular problem, partial sharing buffer based congestion control over ATM networks. Although it is found that the research on such the area has been very fruitful, the approach in this paper is quite exceptional. Instead of using fixed threshold level, we introduce a multi-level threshold strategy which the threshold can be adjusted according to traffic load. This strategy, through dynamically tuning the maximum admissible arrival rate of tagged cells, efficiently balance the overall load of the buffer. So that the buffer performance is consequently improved. Numerical study illustrates that by using our multi-level threshold, the loss probability for priority cells is reduced considerably comparing with the fixed threshold, and at the same time service quality for tagged cells is still guaranteed.

The choice of the thresholds is crucial to both traffic cells. To meet the need of loss probability requirement of tagged cells, the choice of threshold L_c is discovered to be more important than that of others. Given quality constraints of both priority and tagged cells, how to optimally choose the levels of L_o, L_c and L_u can be a further research topic. Hopefully, Nest Threshold proposal [10] may still work in this case.

The decrease of loss probability implies that the buffer is still of potential to support heavier traffic load. Therefore, keeping the loss probabilities at fixed levels, the buffer throughput may accordingly be enhanced, or, the channel bandwidth μ can be saved. All of these indicate that the multi-level load-dependent threshold strategy leads to better buffer performance.

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