On the Impact of Long-Range-Dependent Traffic in Dimensioning ATM Network Buffer *

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Abstract

Recent measurements of packet networks have shown that packet traffic exhibits long-range-dependent property. Studies have also discovered that this property is not adequately captured by the conventional Markov traffic models and often yields queueing behavior such as heavy-tailed or subexponential queue length distribution. These findings have led to the implication that long-range-dependent traffic has a significant impact on determining queueing performance and dimensioning buffer requirement in general.

This paper examines the impact of long-range-dependent traffic on providing connectionless services over ATM networks using AAL5 protocol. As connectionless data packets enter an ATM network, they are encapsulated into AAL5 frames. Within the ATM network, AAL5 frames are segmented into cells for transmission and reassembled at intermediate connectionless servers for frame switching. A queueing model characterizing the AAL5 frame reassembly operation is developed and analyzed to investigate the impact of long-range-dependent traffic on dimensioning the frame reassembly buffer.

The buffer overflow probability is analytically derived. Tight upper bound and lower bound of the AAL5 frame loss probability are also established. The analysis shows that long-range-dependent traffic and conventional Markovian traffic yield similar queueing behavior in the frame reassembly operation.

1 Introduction

Extensive traffic measurements from existing packet networks (including Ethernet LANs, WANs, and VBR video over ATM) have shown that packet traffic exhibits long-range-dependent property [1, 2, 3, 4]. Studies have discovered that the long-range-dependent characteristic plays a significant role in queueing performance as well as in buffer dimensioning of packet networks [5, 6, 7]. The findings in these studies have led many researchers and engineers to believe that the long-range-dependent property will also has critical impact on ATM traffic engineering in all aspects.

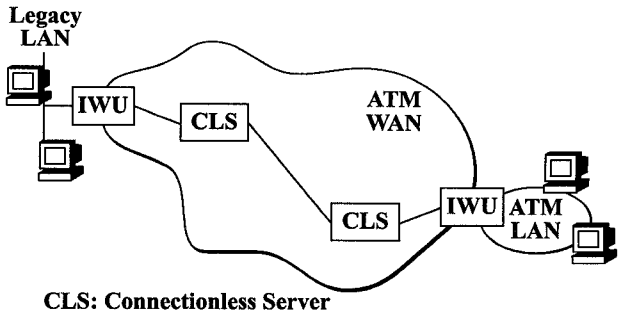

Figure 1: Example of an ATM network environment that supports connectionless services

This paper focuses on determining the role of long-range-dependent traffic in providing connectionless services over ATM networks. In particular, a general queueing model and an analysis framework are developed while assuming a realistic scenario of supporting connectionless services in ATM networks. The importance of long-range-dependent traffic in dimensioning connectionless service buffer is explored.

To study the impact of long-range-dependent traffic in providing connectionless services over ATM network, this paper employs a versatile input process which may be used to generate either long-range-dependent or conventional short-range-dependent traffic. The input process consists of infinite number of independent and identical ON/OFF sources where ON and OFF durations follow respective general distributions. This input process provides a viable alternative to existing traffic models because it is able to express long-range-dependent property and yet mathematically tractable [8]. Although other long-range-dependent traffic models (such as fractional Brownian motion [1, 7] and fractional autoregressive integrated moving-average processes [1]) do exist, they are too computationally intensive to be tractable in general.

*This research is supported by the National Science Foundation through grant NCR-9628109. It has also been supported by grants from the University of California MICRO program, Hitachi Ltd., Hitachi America, Standard Microsystem Corp, Tokyo Electric Power Company, Nippon Telegraph and Telephone Corporation (NTT), Nippon Steel Information and Communication Systems Inc. (ENICOM), and Matsushita Electric Industrial Company.

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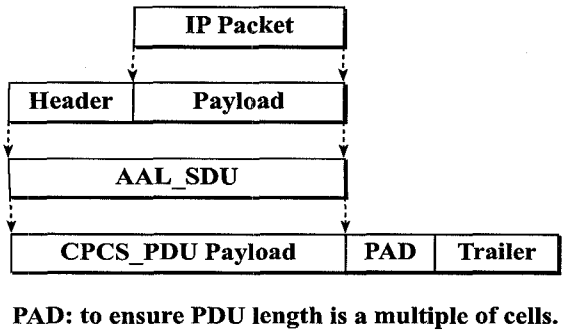

Figure 2: RFC 1483 encapsulation of IP packets

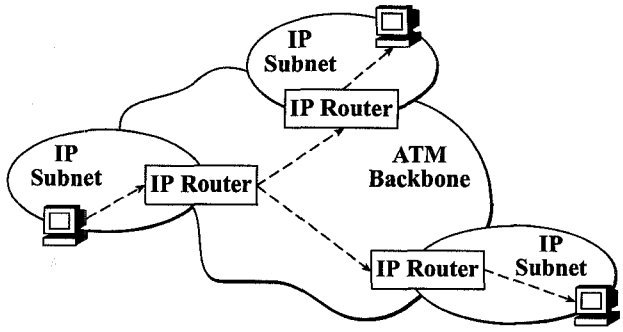

Figure 3: Example of IP over ATM network

In this paper, the importance of long-range-dependent traffic is investigated for an ATM network where connectionless services are supported using AAL5 protocol. As connectionless data packets enter the ATM network, they are encapsulated into AAL5 frames; and AAL5 frames are segmented into cells for transmission. Within the ATM network, cells from various connections are reassembled into AAL5 frames at an intermediate connectionless server or at an internetworking unit before they are forwarded to the next hop server (see Figure 1).

The above scenario considered in this paper characterizes the frame reassembly operation performed in various solutions (e.g. Frame Relay, LAN Emulation, and IP over ATM [9, 10]) to support connectionless services using AAL5 protocol. In IP over ATM, for example, AAL5 provides the equivalent of data link layer services to support IP. As IP packets enter the ATM network, they are encapsulated into AAL5 frames for transmission according to the IETF standard as shown in Figure 2 [11, 12]; and AAL5 frames are segmented into cells for transmission. Within the ATM network, cells from various connections are reassembled into AAL5 frames at an IP router before they are forwarded to the IP router of the next logical IP subnet (see Figure 3).

The buffer space required for the above frame reassembly operation may be large because of the high speed transmission in ATM networks. Consequently, dimensioning the reassembly buffer properly will minimize cell loss and optimize the performance. Buffer requirement for frame reassembly is previously studied in [13] under the assumption of Markovian (exponential) input traffic; no study has assumed realistic long-range-dependent traffic. In addition, frame loss probability is previously studied in [14]. However, the analysis developed in [14] relies on the Markov structure of the input process and thus may not be applied to long-range-dependent traffic.

This paper investigates the importance of long-range-dependent traffic in dimensioning the frame reassembly buffer. The buffer overflow probability is analytically derived. The analysis will show that long-range-dependent and Markovian traffic yield similar queueing behavior for reassembly of AAL5 frames. In addition, tight upper and lower bounds of the AAL5 frame loss probability are obtained.

The rest of the paper is organized as follows. In Section 2, we develop and analyze a general queueing model that characterizes the frame reassembly operation performed at a connectionless server. In Section 3, we demonstrate the importance of long-range-dependent input traffic through numerical examples and simulations results. Finally, conclusions are presented in Section 4.

2 Analysis

In this section, we develop and analyze a queueing model that characterizes the frame reassembly operation performed in various solutions to support connectionless services using AAL5 protocol.

2.1 Queueing Model

This paper considers a general network environment where ATM LANs and various legacy LANs (such as IEEE 802 LANs) are interconnected through a wide area ATM network as shown in Figure 1. Connectionless servers are deployed throughout the ATM backbone to form a virtual connectionless network and to provide packet routing service. In IP over ATM, for example, IP routers form a virtual IP network and provide IP routing service (see Figure 3).

As the connectionless data packets enter the virtual connectionless network within the ATM backbone, they must be adapted to AAL frames at the ATM Adaptation Layer (AAL). The ITU-T has defined two AALs to support connectionless services: AAL3/4 and AAL5 [10]. AAL5 is efficient, simple to implement, and widely adopted among international standard bodies and ATM Forum. This paper assumes that AAL5 is employed to support connectionless services.

There are two proposed methods to forward AAL5 frames in a connectionless server: the stream mode method and the message mode method [10]. The stream mode method is to send cells to the next-hop server or interworking unit as soon as the cells arrive at a server without attempting to accumulate cells and reassemble frames. Because AAL5 lacks the ability to multiplex multiple frames over a single

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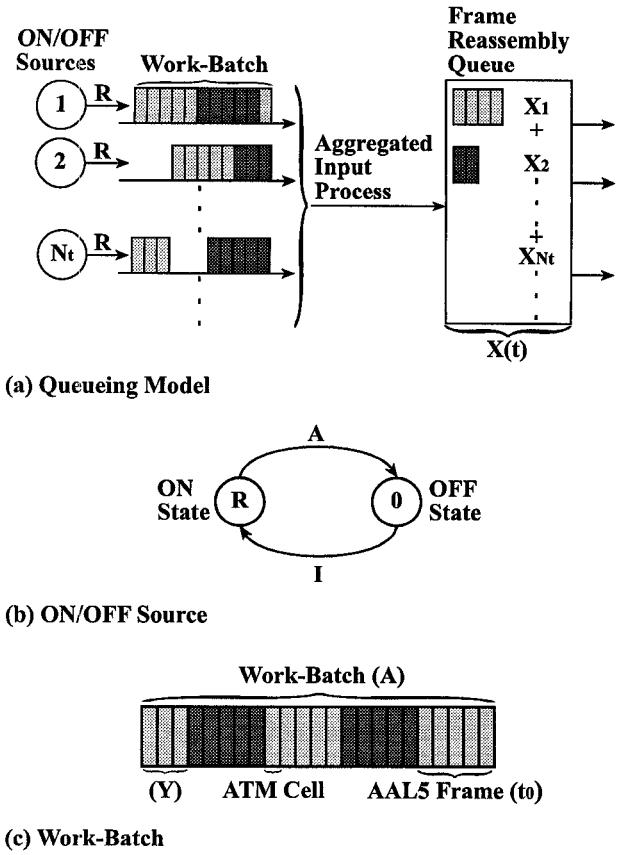

Figure 4: The queueing model: input process and frame reassembly queue

connection, this method requires frame multiplexing to be done on a virtual channel basis with virtual paths serving as dedicated links between network edges or servers. This scheme may not be scalable in large ATM networks where virtual channels and paths are scarce and expensive. The message mode method is to reconstruct AAL5 frames at each connectionless server before frames are resegmented and transmitted to the next hop server or interworking unit.

This paper assumes that AAL5 operates in the message mode to support connectionless service. Consequently, cells from various connections are reassembled into frames at an intermediate connectionless server or an interworking unit before they are forwarded to the next hop server or their destinations. An intermediate connectionless server or an interworking unit which performs the frame reassembly operation is characterized by the queueing model shown in Figure 4(a). The queueing model consists an input process and a frame reassembly queue. The input process assumed in this paper is versatile and may represent both long-range-dependent and short-range-dependent traffic. The frame reassembly queue accumulates arriving cells and reconstructs them into AAL5 frames. Each component of the queueing model is described in detail in the following.

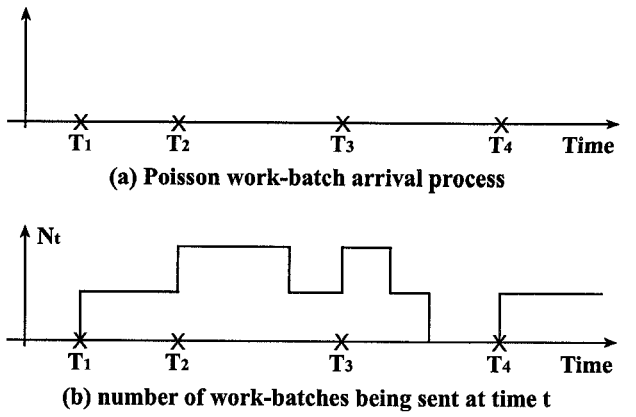

Figure 5: Realization of the Poisson work-batch arrival process and N_t

2.2 Input Process

The input process considered in this paper is versatile and models long-range-dependent traffic as well as conventional short-range-dependent traffic. The input process models the arrival traffic at the frame reassembly queue by aggregating infinite number of independent and identical ON/OFF mini-sources. Each mini-source represents a potential data connection and alternates between ON and OFF states as shown in Figure 4(b). ON and OFF durations follow respective general distributions. A mini-source generates a work-batch during an ON state; no work is generated in an OFF state. Each work-batch represents a bulk of connectionless data.

A Work-batch generated by a mini-source during the ON state is fragmented into AAL5 frames, and the AAL5 frames are segmented into ATM cells as shown Figure 4(c). To simplify the analysis, let's assume that the ATM cells are further segmented into infinitesimal pieces, and the infinitesimal pieces are then sent from the associate mini-source to the frame reassembly queue in sequence. Thus, the infinitesimal pieces arrive at the frame reassembly queue sequentially and continuously at a constant rate R. Note that the work-batch is considered to arrive at the frame reassembly queue at the time instant when its very first infinitesimal piece arrives. Also, note that the fluid queue assumption (where cells are segmented into infinitesimal pieces) provides a reasonable and practical approximation when the cell size is much smaller than the AAL5 frame size.

Suppose that work-batches generated by the aggregated mini-sources arrive at the frame reassembly queue according to a Poisson process with rate λ. A realization of the arrival process is depicted in Figure 5(a). If the arrival time of the n-th work-batch is denoted by T_n, the set of arrival times $\{T_n\}_{n\geq 1}$ forms a Poisson point process. In other words, the time interval between T_{n-1} and T_n follows an exponential distribution such that $P[T_{n+1} - T_n \leq x] = 1 - e^{-\lambda x}$.

The size of a work-batch is a random variable with a general distribution. Let's denote the size of the n-th work-

batch as A_n. We assume the random variables $\{A_n\}_{n\geq 1}$ are independent and identically distributed with a general distribution denoted by $F_A(x) = P[A_n \leq x]$ and a finite mean $E[A] < \infty$. Note that the total time required for the entire n-th work-batch to arrive at the frame reassembly queue is A_n/R. To simplify the presentation, we will assume that $R = 1$ without loss of generality for the rest of Section 2. We also assume that inter-arrival times of work-batches ($\{T_{n+1} - T_n\}_{n\geq 1}$) and work-batch sizes ($\{A_n\}_{n\geq 1}$) are mutually independent.

A work-batch is fragmented into maximum size AAL5 frames followed by a smaller AAL5 frame if necessary (see Figure 4(c)). The maximum AAL5 frame size represents the network maximum transmission unit (MTU) and is denoted by the constant t_0. The number of AAL5 frames contained in a work-batch, K, is a random variable; and its probability mass function and mean are given as follows.

$$P[K = k] = F_A(kt_0) - F_A((k-1)t_0), \tag{1}$$

and

$$E[K] = \sum_{k=0}^{\infty} (1 - F_A(kt_0)) . \tag{2}$$

The state of the aggregated input process is represented by N_t, the number of work-batches arriving at the frame reassembly queue at time t. A sample path of N_t is shown in Figure 5(b). The stochastic behavior of N_t is identical to the number of busy servers at time t in a $M/G/\infty$ queue [6]. The Poisson arrival of the $M/G/\infty$ queue corresponds to the Poisson arrival of work-batches. The general service time distribution G of the $M/G/\infty$ queue corresponds to the general distribution of the work-batch size. Finally, the infinite servers of the $M/G/\infty$ queue correspond to the infinite ON/OFF mini-sources and imply that each work-batch sent from the mini-source always arrives at the frame reassembly queue. We will refer the aggregated input process as the $M/G/\infty$ process for the rest of the paper.

It is well known that N_t has a Poisson marginal distribution in the steady state [15] such that

$$P[N_t = k] = \frac{(E[N_t])^k}{k!} e^{-E[N_t]}, \tag{3}$$

where

$$E[N_t] = \lambda E[A]/R. \tag{4}$$

The autocovariance function $r(\tau)$ of the N_t is also known as the following [15]:

$$r(\tau) = cov\{N_t, N_{t+\tau}\} = \lambda \int_{\tau}^{\infty} 1 - F_A(x)dx. \tag{5}$$

The $M/G/\infty$ process provides a viable alternative to existing traffic models for the following reasons. Firstly, equation (5) shows that traffic with temporal correlations over a wide range of time scales may be modeled simply by controlling the tail behavior of the general distribution $F_A(x)$. For example, if the distribution $F_A(x)$ is heavy-tailed (exponential), then the $M/G/\infty$ process is long-range-dependent (short-range-dependent) [2]. Secondly, the $M/G/\infty$ process has been shown to successfully model some wide area data applications such TELNET and FTP [2]. Thirdly, the $M/G/\infty$ process is a mathematically tractable model.

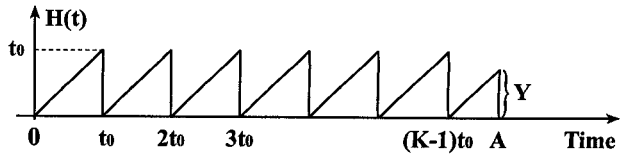

Figure 6: Realization of $H(t)$

2.3 Frame Reassembly Queue

The main function of the frame reassembly queue is to accumulate and reassemble the cells into their corresponding AAL5 frames. Recall that a work-batch is fragmented into AAL5 frames, the AAL5 frames are segmented into ATM cells, the ATM cells are further segmented into infinitesimal pieces, and the infinitesimal pieces arrive the frame reassembly queue sequentially and continuously at a constant rate R. As shown in Figure 4(a), when an entire AAL5 frame is received by the frame reassembly queue, it is reassembled and then removed from the frame reassembly queue for resegmentation and transmission to the next hop server. At the same time instance, the accumulation of the infinitesimal pieces belonging to the subsequent AAL5 frame begins at the frame reassembly queue.

Two performance measures are obtained for the infinite buffer frame reassembly queue: buffer overflow probability and AAL5 frame loss probability. Throughout this paper, buffer overflow probability is defined as the probability that buffer occupancy exceeds a certain threshold value in an infinite buffer system. The buffer overflow probability provides an upper bound to the loss probability of the corresponding finite buffer system [16]. During the period which the buffer occupancy exceeds the threshold value, arriving cells are marked, and AAL5 frames with marked cells are considered lost. The AAL5 frame loss probability is defined as the ratio between the number of lost frames and the number of frame arrived in the steady state.

2.3.1 Buffer Overflow Probability

Suppose that a work-batch of size A arrives at the frame reassembly queue at time $t = 0$. The work-batch is fragmented into K number of AAL5 frames: $K - 1$ number of maximum size (t_0) frames followed by the K-th frame with size $Y = A - (K-1)t_0$. Note that Y is a random variable and $Y \leq t_0$. As shown in Figure 6, the buffer space required to store an arriving work-batch at the frame reassembly queue, $H(t)$, increases linearly with slope $R = 1$ when an AAL5 frame belonging to the work-batch is being received and accumulated. When the entire AAL5 frame is received, it is reassembled and immediately removed from

the frame reassembly queue; and $H(t)$ decreases to 0. Note that $H(t)$ follows a uniform distribution between 0 and t_0 when $t \in [0, (K-1)t_0]$, and $H(t)$ follows the *residual life* distribution of Y when $t \in ((K-1)t_0, A]$ [15].

Based on the discussion in the last paragraph, the probability density function of $H(t)$ becomes the weighted sum of the uniform density function over the $(0, t_0)$ interval and the residual life density of Y, and is given by the following.

$$\begin{aligned} f_H(x) &= \frac{E[K]-1}{E[K]}\frac{1}{t_0}(u(x)-u(x-t_0)) + \frac{1}{E[K]}\frac{P[Y>x]}{E[Y]} \\ &< \frac{1}{t_0}(u(x)-u(x-t_0)), \end{aligned} \tag{6}$$

where $u(t)$ is the unit step function, and $E[K]$ is given in equation (2). The inequality in the above equation follows the fact that $Y < t_0$. Also, the inequality serves as a good approximation of the density function because majority of the weight $(\frac{E[K]-1}{E[K]})$ is at the uniform density function.

Recall that work-batches arrive at the frame reassembly queue according to a Poisson point process, $\{T_n\}_{n\geq 1}$. The total buffer space required to store all of the arriving work-batches at the frame reassembly queue at time t, $X(t)$, is obtained by summing the buffer space required to store each arriving work-batch at time t as follows;

$$X(t) = \sum_{i=1}^{\infty} H(t-T_i). \tag{7}$$

To determine the density $f_X(x)$ of $X(t)$ in the steady state, we apply the well known shot noise analysis [17] and obtain

$$f_X(x) = \delta(t)P[N_t=0] + \sum_{k=1}^{\infty} f_H^{(k)}(x)P[N_t=k], \tag{8}$$

where $f_H^{(k)}(x)$ is the k-fold convolution of $f_H(x)$, and $P[N_t = k]$ is given in equation (3).

To calculate $f_H^{(k)}(x)$, we invert the k-th power of the Laplace transform of equation (6) and obtain

$$f_H^{(k)}(x) = \sum_{n=0}^{k} \binom{k}{n} \frac{(-1)^n}{t_0^k} \frac{(x-nt_0)^{k-1}}{(k-1)!} u(x-nt_0). \tag{9}$$

The buffer overflow probability then becomes

$$P[X(t)>x] = \sum_{k=1}^{\infty}(1-F_H^{(k)}(x))P[N_t=k], \tag{10}$$

where $F_H^{(k)}(x) = \int_0^x f_H^{(k)}(y)dy$.

2.3.2 Frame Loss Probability

The period during which $X(t)$ exceeds the threshold value, B, is called a loss period. During the loss period, arriving cells are marked, and AAL5 frames with marked cells are considered lost. In this section, we derive the AAL5 frame loss probability. We first define

$F(t)$ = the number of AAL5 frames lost in the time interval $[0, t]$,

$A(t)$ = the number of AAL5 frames arrived in the time interval $[0, t]$.

Then, the frame loss probability Φ is given by

$$\Phi = \lim_{t\to\infty} \frac{F(t)}{A(t)} = \frac{\lim_{t\to\infty}\frac{F(t)}{t}}{\lim_{t\to\infty}\frac{A(t)}{t}} = \frac{E[F(t)]}{E[A(t)]}, \tag{11}$$

assuming the limits exist.

To calculate Φ, we will derive $E[F(t)]$ and $E[A(t)]$ in the following. Let's define $n(t)$ and f_i as follows;

n(t) = the number of loss periods in the time interval $[0, t]$,

f_i = the number of AAL5 frames lost in the i-th loss period in the time interval $[0, t]$.

Then,

$$\begin{aligned} E[F(t)] &= \lim_{t\to\infty}\frac{1}{t}F(t) \\ &= \lim_{t\to\infty}\frac{1}{t}\sum_{i=1}^{n(t)} f_i \\ &= \lim_{t\to\infty}\frac{\sum_{i=1}^{n(t)} f_i}{n(t)} \lim_{t\to\infty}\frac{n(t)}{t} \\ &= E[f]\lim_{t\to\infty}\frac{n(t)}{t}, \end{aligned} \tag{12}$$

where $E[f]$ is the average number of frames lost in a loss period. Also,

$$E[A(t)] = \lim_{t\to\infty}\frac{1}{t}A(t) = \lambda E[K]. \tag{13}$$

Therefore, by substituting equations (12) and (13) into (11), we obtain Φ as follows;

$$\Phi = \frac{E[f]}{\lambda E[K]}\lim_{t\to\infty}\frac{n(t)}{t}. \tag{14}$$

We first obtain $E[f]$, the average number of frames lost in a loss period, in equation (14). At the start of the loss period, the frames which are being received may be lost. In addition, new frames that arrive during the loss period will cause the loss of additional frames. In the case where frame loss is maximum, all frames being received during the loss period are lost. Conversely, since the buffer can accommodate up to $c = \lfloor B/t_0 \rfloor$ arriving frames, these c frames won't be affected in the case where frame loss is minimum. In reality, the number of affected frames is between these two limiting values.

Following the heuristic reasoning in the last paragraph, we have

$$E[f]\begin{cases} \leq & (\lambda E[L] + E[N_t|X(t)=B])(1+\frac{E[L]}{t_0}) \\ \geq & (\lambda E[L] + E[N_t|X(t)=B] - c)(1+\frac{E[L]}{t_0}), \end{cases} \tag{15}$$

where $\lambda E[L]$ is the average number of work-batches that arrive during a loss period, $E[N_t|X(t) = B]$ is the average number of work-batches arriving at the frame reassembly queue at the start of a loss period, and $1 + \frac{E[L]}{t_0}$ is the average number of frames arrived during a loss period per work-batch. Note that the bounds in equation (15) are not tight in general. For example, if the frame reassembly queue alternates between loss period and non-loss period at a high frequency, then an arriving frame may experience more than one loss period and thus may be considered lost more than once in our analysis. However, the bounds in equation (15) are certainly tight in the asymptotic sense (i.e. when frame loss probability is small and approaches 0 or equivalently when loss periods and non-loss periods alternate at a low frequency).

$E[N_t|X(t) = B]$ is given by the following equation.

$$\begin{aligned} E[N_t|X(t) = B] &= \sum_{k=0}^{\infty} kP[N_t = k|X(t) = B] \\ &= \frac{\sum_{k=1}^{\infty} kf_H^{(k)}(B)P[N_t = k]}{f_X(B)}, \quad (16) \end{aligned}$$

where $f_X(x)$ and $f_H^{(k)}(x)$ are given in equations (8) and (9), respectively.

We next calculate $E[L]$ and $\lim_{t\to\infty} \frac{n(t)}{t}$ in equation (14) to obtain the frame loss probability, Φ. Note that $E[L]$ is the average length of the loss periods. We first define

L_i = Length of the i-th loss period.

The fraction of time the queue spent in loss periods during an time interval of length t converges to the probability that the buffer occupancy exceeds the threshold value B as t approaches to infinity (namely, the buffer overflow probability obtained in Section 2.3.1). Therefore, we have

$$\lim_{t\to\infty} \frac{\sum_{i=1}^{n(t)} L_i}{t} = P[X(t) > B]. \quad (17)$$

Rearranging terms in the above equation, we obtain

$$\begin{aligned} P[X(t) > B] &= \lim_{t\to\infty} \frac{\sum_{i=1}^{n(t)} L_i}{n(t)} \times \lim_{t\to\infty} \frac{n(t)}{t} \\ &= E[L] \lim_{t\to\infty} \frac{n(t)}{t}. \quad (18) \end{aligned}$$

Therefore,

$$E[L] = \frac{P[X(t) > B]}{\lim_{t\to\infty} \frac{n(t)}{t}}. \quad (19)$$

Note that $\lim_{t\to\infty} \frac{n(t)}{t}$ is the occurrence frequency or the arrival rate of the loss period. $\lim_{t\to\infty} \frac{n(t)}{t}$ is also equivalent to the frequency of $X(t)$ exceeding the threshold value, B, because the buffer occupancy $X(t)$ will exceed B at the start of each loss period. We employ the level crossing analysis developed in [17] and obtain

$$\begin{aligned} \lim_{t\to\infty} \frac{n(t)}{t} &= E[N_t|X(t) = B]f_X(B) \\ &= \sum_{k=1}^{\infty} kf_H^{(k)}(B)P[N_t = k]. \quad (20) \end{aligned}$$

Substituting equations (15) and (20) into equation (14), we finally obtain the AAL5 frame loss probability Φ.

3 Numerical Results

This section presents numerical results to investigate the impact of long-range-dependent traffic on the buffer requirement at the frame reassembly queue. We numerically obtain the buffer overflow probability and the frame loss probability of the frame reassembly queue given in equation (10) and (14), respectively. In addition, numerical values obtained through the analysis are validated by simulations. Numerical results show that long-range-dependent traffic only has slight impact on dimensioning the frame reassembly buffer due to the segmentation of connectionless data into fixed size AAL5 frames.

In the following numerical examples, we will consider two cases of the $M/G/\infty$ process described in Section 2.2: $M/M/\infty$ process and $M/P/\infty$ process, where the corresponding $F_A(x)$ are exponential ($F_{A_e}(x)$) and Pareto ($F_{A_p}(x)$), respectively. The $M/M/\infty$ process is Markovian (short-range-dependent), and

$$F_{A_e}(x) = 1 - \exp(\frac{-x}{E[A_e]}), \qquad \text{for } x \geq 0.$$

On the other hand, the $M/P/\infty$ process is a long-range-dependent process with *Hurst parameter*, $H = \frac{3-\alpha}{2}$ ($\frac{1}{2} < H < 1$)) [6], and

$$F_{A_p}(x) = 1 - \frac{\beta^\alpha}{(x+\beta)^\alpha},$$

for $1 < \alpha < 2$, $\beta > 0$, $x \geq 0$.

$$E[A_p] = \frac{\beta}{\alpha - 1}.$$

The Hurst parameter is designed to capture the degree of long-range-dependence. The larger the value of the Hurst parameter is, the higher the degree of the long-range-dependence is.

The queueing behaviors of the frame reassembly queue under the following input processes are compared: a $M/M/\infty$ process and two $M/P/\infty$ processes. The corresponding Hurst parameters of the two $M/P/\infty$ processes are $H_1 = 0.75$ and $H_2 = 0.55$, respectively. Note that the $M/P/\infty$ process with $H_1 = 0.75$ has the highest degree of long-range-dependence among the input processes. We also

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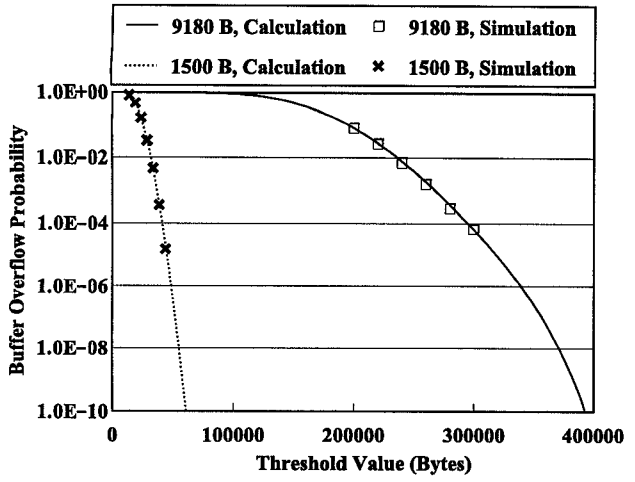

Figure 7: Buffer overflow probability ($M/P/\infty, H = 0.55$)

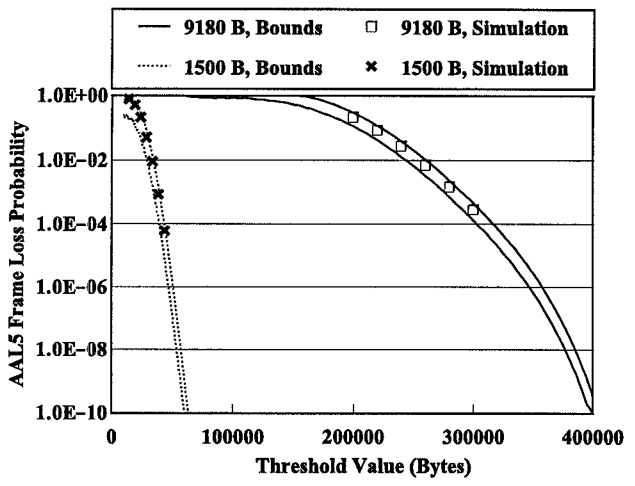

Figure 8: AAL5 frame loss probability ($M/P/\infty, H = 0.55$)

assume that the average work-batch size ($E[A]$) is 15000 bytes. The average work-batch arrival rate (λ) is assumed to be 1000 work-batches per second.

To investigate the effect of the maximum AAL5 frame size (namely, t_0) on the buffer requirement of the frame reassembly queue, we will consider two maximum AAL5 frame sizes of 1500 bytes and 9180 bytes. The maximum AAL5 frame sizes of 1500 bytes and 9180 bytes correspond to the maximum transmission unit of Ethernet and IP-over-ATM, respectively [11]. We use the $M/P/\infty$ process with $H_2 = 0.55$ in this set of investigation. Figure 7 shows the buffer overflow probability versus the threshold value for both maximum frame sizes. Note that the numerical calculations agree with the simulation results. Figure 8 shows the frame loss probability. The simulation points lie between the two analytical bounds obtained through the analysis developed in Section 2.3.2. Figure 8 indicates that in the range of interest, the actual frame loss probability is close to the

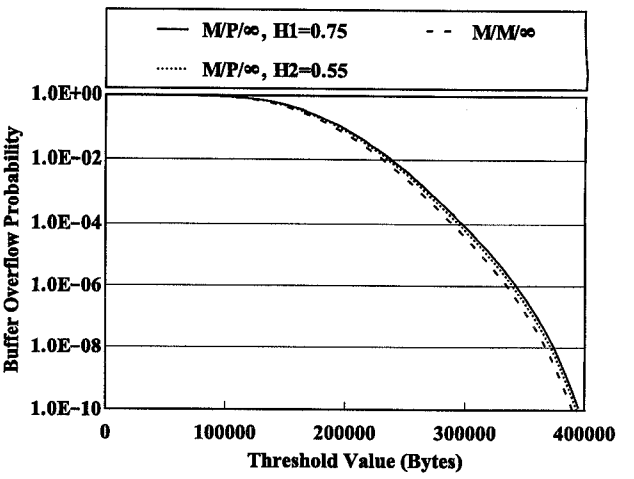

Figure 9: Buffer Overflow Probability ($t_0 = 9180$ Bytes)

upper bound when no cell discarding schemes are employed.

Both Figures 7 and 8 show that the maximum AAL5 frame size has a significant impact on the buffer requirement of the frame reassembly queue. These two figures suggest that smaller maximum AAL5 frame size will result in less buffer space requirement. The smaller maximum size AAL5 frames require less buffer space to accumulate their cells for reassembly because they contains less cells. For example, Figure 7 shows that to achieve buffer overflow probability of 1^{-10}, the frame reassembly queue requires buffer space of approximately 60000 bytes when the maximum frame size is 1500 bytes. In contrast, when the maximum frame size is 9180 bytes, the frame reassembly queue would now require approximately 390000 bytes (6.5 times) of buffer space to achieve the same overflow probability.

We next explore the impact of long-range-dependent traffic on the buffer requirement of the frame reassembly queue. Figure 9 shows the buffer overflow probability for the $M/M/\infty$ and the two $M/P/\infty$ processes when the AAL5 frame size is 9180 bytes. Note that the three curves are close to each other and exhibit similar tail behavior. This observation indicates that the long-range-dependent property (or the heavy tail characteristic) has virtually no impact on the reassembly queue buffer requirement. The long-range-dependent (heavy tail) effect diminishes when connectionless data are segmented into fixed size AAL5 frames. This can also be seen from equation (10), where the tail behavior of the buffer overflow probability is dominated by $f_H^{(k)}(x)$ in equation (9). The lower bounds and upper bounds of the frame loss probability are shown in Figure 10 and 11, respectively, where we observe similar tail behavior for all three input processes.

4 Conclusion

This paper studies the importance of long-range-dependent traffic in the buffer requirement of providing connection-

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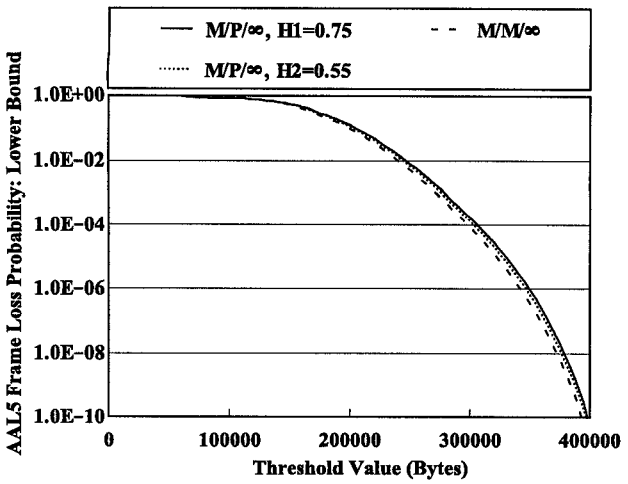

Figure 10: Lower Bound of the AAL5 frame loss probability ($t_0 = 9180$ Bytes)

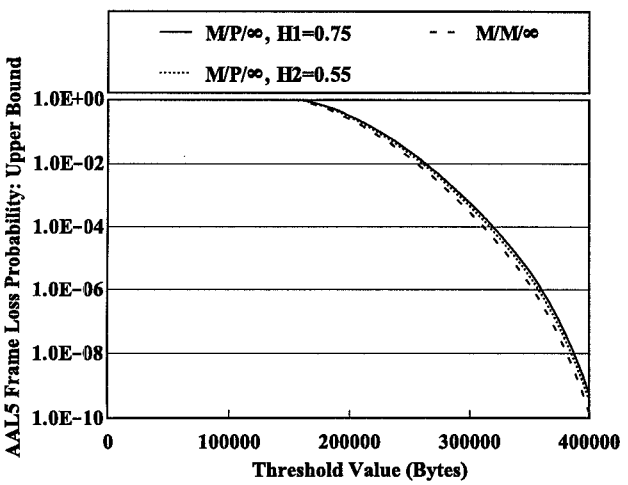

Figure 11: Upper Bound of the AAL5 frame loss probability ($t_0 = 9180$ Bytes)

less services using ATM AAL5 protocol. A queueing model which characterizes the frame reassembly operation performed by the AAL5 protocol is developed and analyzed. Buffer overflow probability and tight bounds for the AAL5 frame loss probability are obtained. The bounds are useful in determining the limit of selective cell discarding schemes. The results show that long-range-dependent traffic and Markovian traffic yield similar queueing behavior in the frame reassembly operation.

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