Comparative Performance of Scheduling Strategies for Switching and Multiplexing in A Hub Based ATM Network: A Simulation Study

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Abstract

We model an ATM network comprising an *input queuing* cell switching hub. Customer access lines are multiplexed into the relatively faster input links of this hub. Each access multiplexer is fed by on/off sources. Motivated by the fact that an ATM network should support both bursty as well as smooth traffic, we consider the scenario in which some multiplexers are fed by sources with long bursts of cells, and others by sources with short bursts. Here we report the results of a detailed simulation of this hub-based ATM network. Our objective is to compare the performance of various strategies for scheduling cell service in the access multiplexers, and in the ATM switch. The simulation results confirm what might be expected from the results of our earlier analytical modelling of the multiplexer and the switch *in isolation* (this analysis assumed a particular Markovian model for the aggregate cell arrival processes into the ATM switch).

In particular, we find that, if mean burst delay is the performance criterion then, for a small ratio of ATM-link to customer-access-line speed (≤ 3 for the models and parameters we use), the more bursty traffic should undergo *burst level multiplexing* at the access multiplexer, and should be given *lower priority* during output contention resolution in the input queueing hub. If worst case delay performance (e.g., the 99.9 percentile of the end-to-end delay of a burst) is a consideration, however, we find that, even for small ATM-link to access-line speed ratio, the best combination of strategies is that the access multiplexers should multiplex the packets from the access lines in a *round-robin* fashion, and the switch should still give lower priority to the burstier traffic.

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Keywords: input queueing ATM switches, playout buffering, cell jitter effects, round-robin multiplexing, noninterleaved multiplexing

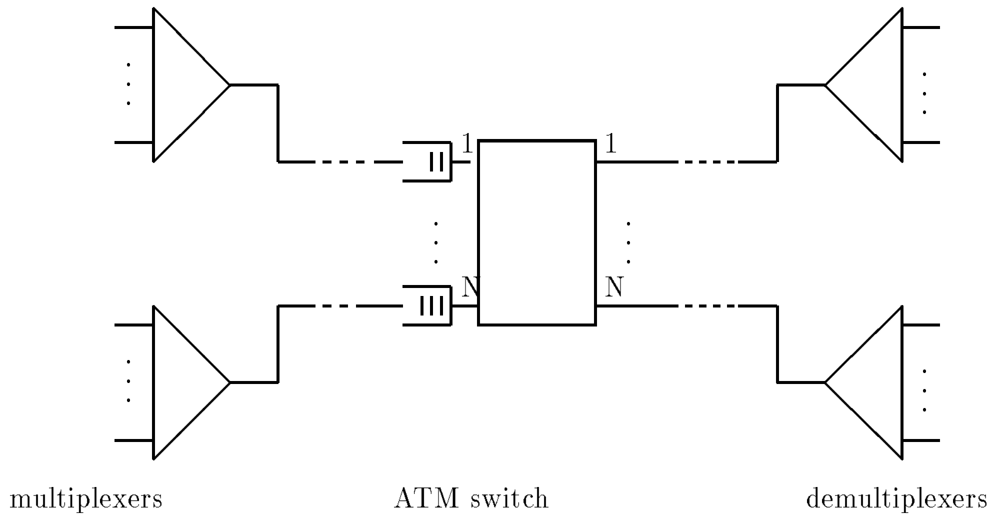

Figure 1: An ATM network with an input queueing cell switching hub and access multiplexers/demultiplexers

1 Introduction

In this paper we present the results of a simulation study of a network comprising an ATM cell switching hub whose input links are fed by the outputs of ATM cell multiplexers, as shown in Figure 1. The hub is an input queuing nonblocking cell switch. The traffic at the inputs to the multiplexers consists of bursts of ATM cells, obtained by "cellising" the bits from variable bit rate (VBR) sources.

Our main objective in this work is to perform a comparative study of scheduling strategies in the switch and in the multiplexers. Analytical studies of these strategies, with the network elements (i.e., multiplexer or switch) in isolation, have been performed elsewhere (see [16], [12], [13], [14]). In this paper, we combine these network elements into a simple hub based network and perform a simulation study of end-to-end delay performance with various combinations of scheduling strategies at the multiplexers and the switch.

In the context of the input queuing cell switch, we are interested in the scenario in which traffic on the input links displays serial correlation in the selection of an output link (we shall generally refer to serial correlation as source *burstiness*). The traffic on different links, however, differs in the degree of serial correlation. Here we are motivated by the fact that a "local access" ATM switch will receive traffic from Metropolitan Area Networks (MANs) and also directly from Broadband ISDN (B-ISDN) terminals ([2]). It can be expected that since MANs aggregate traffic from relatively slow sources, the cells on ATM links emanating from MANs will display low serial correlation in their demands for output links. The traffic from a B-ISDN terminal (e.g., a HDTV source), however, can be expected to display high serial correlation, even to the extent of delivering consecutive cells destined for the same output. Motivated by this situation, we have analysed the performance of an input queuing ATM switch in which some input processes display low serial correlation and others high serial correlation ([13], [14]). For a particular Markov model for traffic on the input links, we have shown that when Head-Of-the-Line (HOL) cells at two or more input links contend for the same output link then the throughput and the delay performance can be improved by giving priority to contending cells belonging to input links with low serial correlation. For this analytically tractable traffic model a detailed saturation throughput analysis and delay analysis have been performed for the priority scheduling scheme ([13], [14]).

In the present paper we are interested in studying the performance of the above mentioned scheduling strategy with more realistic traffic processes at the input links of the hub. We obtain these traffic processes as the outputs of cell multiplexers whose inputs are fed by simple on-off cell traffic processes. Even at the multiplexers several scheduling strategies are possible. In particular, we have studied noninterleaved multiplexing, in which cells from bursts on different access lines are not interleaved, and interleaved multiplexing [16]. The motivation for studying these schemes is that for isochronous sources (e.g., VBR video), there is a need to keep the cells within bursts together (i.e., avoid a large cell *jitter* within a burst), as large variability of cell delay within a burst will necessitate a large playout delay. We show analytically that, for a particular model for cell arrivals, there is a threshold of ATM trunk-speed to customer access-line-speed ratio (3 for the particular model we have analysed) below which burst level (or noninterleaved) multiplexing is better for minimising mean end-to-end burst delay.

The analyses of the multiplexers and the switch, in isolation, can be used to make inferences about the best scheduling strategies to use in the network context. We get several combinations of multiplexing and switching strategies. Our objective in this paper is to use simulation to study the various possibilities, and compare the results in the network with the results from the analyses of the components in isolation.

The outline of this paper is as follows. In Section 2 we give a summary of the results of our analytical study of the switch in isolation. Section 3 provides the details of the comparison of two multiplexing strategies for the access multiplexer in isolation. We present the simulation study of the hub based ATM network in Section 4, and we conclude in Section 5.

2 Switching of Multiclass Bursty Traffic in an Input Queuing ATM Switch

2.1 HOL Blocking

We consider an $N \times N$ nonblocking space-division ATM cell switch [9, 8]. We assume that it operates in a slotted, synchronous fashion, i.e., the switch inputs are slotted and the slot boundaries on different switch inputs coincide. Buffering of cells within the switch must be provided because of the *output conflicts.* Though there are various approaches for providing the queuing necessary [7], we consider input queuing in which case a separate buffer is placed on each input to the switch. Also FIFO discipline is considered for admitting cells queued at the input buffers. Although very simple, the main problem with FIFO is *HOL blocking.* While a cell is waiting its turn for access to an output, other cells may be queued behind it in the FIFO and are, consequently, blocked from reaching possibly idle outputs on the switch.

2.2 Input Traffic Model

Performance analysis of such ATM switches have been done with various traffic assumptions [9, 7, 15, 4, 17, 18, 13]. Studies in [9, 7, 15, 4] were based on a Bernoulli model for cell arrivals, each cell independently requesting each output with equal probability. S.Q.Li [17] studied the switch performance under independent but nonuniform traffic (i.e., the routing probabilities of cells to outputs are unequal). Performance analysis with correlated input traffic has been reported in [18]. An "on-off" cell arrival model, with geometric burst lengths, has been used in [5]. In all these studies it is assumed that the traffic on each input link has the same statistical behaviour. Also, Random Selection (RS) contention resolution policy is used, i.e., among the k HOL cells contending for the same output, one cell is randomly selected with probability $1/k$ for transmission across the switch fabric in one slot time.

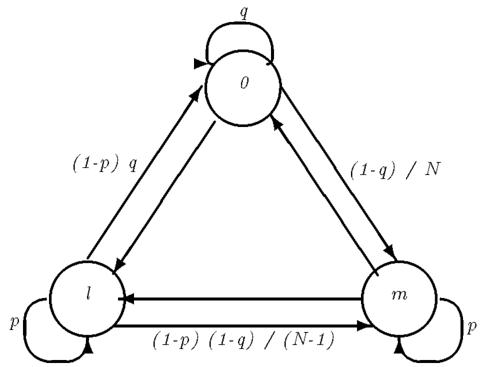

Figure 2: Markov chain transition diagram for the cell arrival process at each input; only the transitions between two states l and m and the idle state 0 are shown.

In an ATM network, however, the traffic on some inputs of the local access hub will display high serial correlation in their demands for output links compared to traffic on other inputs, as mentioned in the Introduction. In this context the following traffic model used in [13, 14] is interesting.

At each input, the cell arrival process is characterized by an $N+1$ state Markov chain $\{\xi_n, n \geq 1\}$ whose transition probabilities are depicted in Figure 2. The state ξ_n represents the destination address of the cell that arrives in the n-th slot. Only 3 of the possible states of this process, and the transitions between them are shown in the figure. Thus if $\xi_n = l \ or \ m, \ 1 \leq l, m \leq N$, then a cell destined for that output arrives in the n-th slot; whereas $\xi_n = 0$ denotes that the n-th slot is empty. The transition probabilities in Figure 2 can be understood from the following. With probability p, a cell destined for a particular output is followed by *another* cell for the same output. Hence the number of consecutive slots with cells for the same output has a geometric distribution with mean $1/(1-p)$. We refer to this batch of consecutive cells destined for the same output as a "burst" of cells for that output. With probability $(1-p)q$ a burst for output l is followed by an empty slot and, with probability $(1-p)(1-q)$ it is followed by a cell for a new output. This new output is chosen uniformly from among the $(N-1)$ outputs (i.e., excluding l). The slot following an empty slot is again empty with probability q, thus giving rise to a geometrically distributed "idle" period. With probability $(1-q)/N$ an idle period is followed by a burst for one of the N outputs. The arrival process at each input is characterized by one such Markov chain. *The different inputs may have different values for the burst-length parameter p.*

2.3 A Priority Selection HOL Contention Resolution Policy

We have proposed a priority selection HOL contention resolution policy in the context of the above mentioned mixed (multiclass) bursty traffic [13, 14]. In the case of two traffic classes, when HOL cells on two or more input links contend for the same output link then we propose to give priority to contending cells belonging to input links with low serial correlation. We call this the Shorter-Expected-Burst-length-First (SEBF) scheme. The intuitive idea behind the possibility of improved performance with this priority selection scheme is that, by giving priority to the inputs with shorter bursts, contention for an output is likely to be broken earlier than if priority was given to inputs with longer bursts. In the next section we give the summary of results of the asymptotic ($N \to \infty$) throughput analysis [12, 13] and burst delay analysis [14].

2.4 Saturation Throughput and Mean Burst Delay for Two Classes with Priority

A fraction α of the N inputs have traffic with mean burst length $1/(1-p_1)$ (called type 1 inputs) and the rest of the inputs have traffic with mean burst length $1/(1-p_2)$ (called type 2 inputs). Output contention is always resolved in favour of type 1 inputs. Random selection is used within a type. We consider the asymptotic case, i.e., $N \to \infty$.

An input queue is said to be *saturated* if after a head-of-the-line (HOL) cell is transmitted from this queue, there is always a cell queued behind it waiting to take the HOL position, i.e., the input buffer is never empty. The *saturation throughput* of the switch is the rate at which cells are switched onto the output links when all the input queues are saturated.

Summarizing the results of our analytical study for the asymptotic case, and the simulation study for finite switch size [12, 13], we have the following observations. There is dramatic improvement in saturation throughput with priority given to the less bursty tarffic (i.e., SEBF) over the case with priority given to more bursty traffic (i.e., Longer-Expected-Burst-length-First or LEBF). Further, if priority is given to the class with shorter expected burst lengths then the total saturation throughput of the switch is more than if all the traffic was of this class. On the other hand if priority is given to the class with larger expected burst lengths then the total throughput is less than if all the traffic was of this class.

These observations can be intuitively understood as follows. From the point of view of HOL contention, burstiness has an advantage and a disadvantage. If the traffic is bursty then contention can last a long time; this is the disadvantage. However, if several bursty inputs are feeding bursts to *distinct* outputs then sustained throughput can be obtained for some time; this is an advantage. Random traffic (i.e., traffic of low burstiness) tends to cause frequent HOL conflicts of short duration. When we have a mix of these two types of traffic then giving HOL priority to the less bursty input class results in blocking of low priority HOL cells for short periods only. Since a lower priority input class is more bursty it will not get into contention frequently with other inputs of its own class. Thus better throughputs of both classes can be obtained. For a detailed analysis and numerical results, see [13].

The *burst delay* at an input queue is defined as the time from the first cell of the burst arriving at the input buffer, until the last cell of the burst is transmitted across the switch fabric to the output link. Detailed analysis for burst delays for two classes with priority is given in [14]. Summarizing the results, there are combinations of cell arrival rates for the two bursty classes such that while both type 1 (less bursty) and type 2 (more bursty) input queues are stable with SEBF policy, type 1 queues are unstable with reversed priority; further, the degradation of type 2 mean burst delay with SEBF when compared to LEBF is not significant. Thus without significantly affecting the delay performance of type 2 traffic, that of type 1 traffic is improved drastically.

Throughput analysis as well as delay analysis with the random selection (RS) rule for two classes are intractable; see, however, [3] for a recent approximation approach. Our simulation study for finite N [14], and analysis for $N = 2$ [12], show that SEBF yields better performance than RS, and LEBF yields worse performance than RS.

3 Multiplexing of Bursty Traffic

The traffic on a link at an ATM switch will typically be obtained by multiplexing traffic from sources connected to the network via lower speed access links; e.g., 1.5 Mbps, 45 Mbps or 150 Mbps access links, feeding a 600 Mbps link via a cell multiplexer.

High quality communication and distribution video services all use codecs that pro-

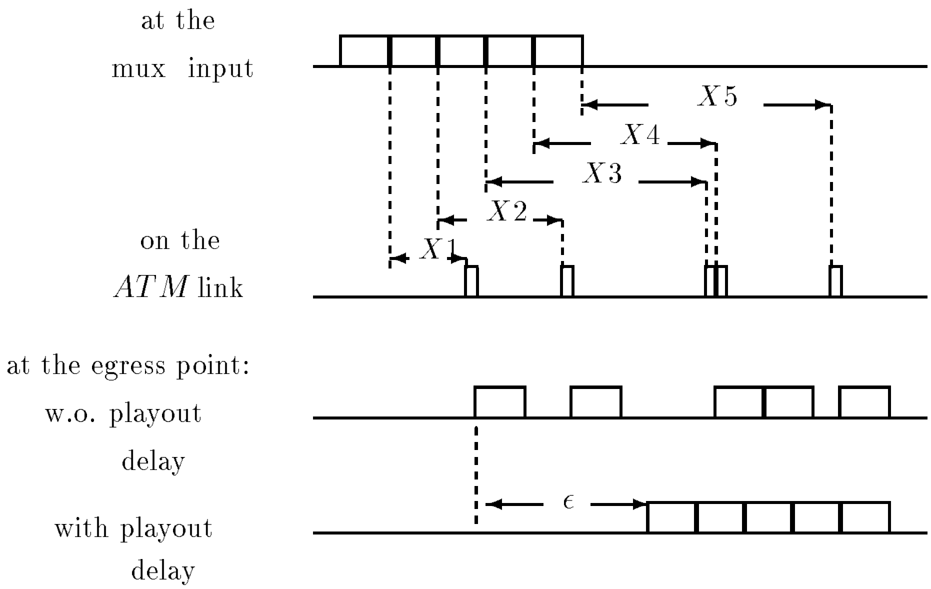

Figure 3: Illustration of burst expansion in round-robin scheme when $M > c$

duce a variable rate output. These VBR sources feeding into an ATM "cellizer" will yield an on-off pattern of cells on the ATM access link.

We analyse a multiplexer multiplexing M statistically identical on-off VBR sources on to an ATM link. We assume that each access line carries a single VBR connection. For analytical tractability we assume geometrical on and off periods. For sources like VBR video there is a need to keep the cells within bursts together; otherwise, variability of cell delay (or *jitter*) within a burst will necessitate a playout delay to deliver a continuous burst at the receiving point. In a similar situation Kumar and Cole [16] identified two ways of multiplexing traffic from the various access lines. They compared the performance of two service disciplines that an ATM Terminal Adapter can use to multiplex pipelined synchronous protocol frames arriving over low speed lines. We examine those two multiplexing strategies in the present context of high speed access and trunk lines.

3.1 Burst and Cell Level Multiplexing

(i) *Burst level multiplexing:* The bursts arriving over low speed access lines are queued in their order of arrival in a commonly shared buffer. These bursts are transmitted on the ATM link in a FIFO order. If the burst currently being served has not fully arrived at the buffer, then the trunk server waits for the subsequent cells of the burst to accumulate. In this scheme, cells from bursts on different input lines are not interleaved. This minimises the delay "jitter" of cells *belonging to the same burst*, and hence burst level multiplexing seems to be the most appropriate strategy for services like VBR video. However, the trunk utilization is inefficient.

(ii) *Cell level multiplexing:* Rather than buffering and serving bursts in their order of arrival, cells are queued up and served in their order of arrival. Though this can be done in different ways, we consider the round robin scheme where there are local buffers for storing cells from each line which are served in a round robin fashion by the trunk server. In this scheme, cells from bursts on different input lines will be interleaved which can result in large delay jitter of cells belonging to the same burst. Figure 3 illustrates how cell level multiplexing can lead to burst expansion when $M > c$, where c is the trunk speed to access line speed ratio. Figure 3 also illustrates the need for a playout delay at the receiving end to deliver a continuous burst. If X_n denotes the time interval from the arrival of the last bit of n-th cell at the multiplexer until the transmission of its first bit on the ATM link then the burst expansion ϵ is given by $\epsilon = \max_k(X_k - X_1)$ [12]. However, by not forcing the trunk to be idle while successive cells of a burst accumulate over the low speed line, the trunk utilization is better.

3.2 Analysis of Burst Level Multiplexing

We use a fluid flow approximation: there is no notion of discrete cells, and approximate the burst size to an exponentially distributed random variable. This approximation is valid provided the average number of cells per burst is sufficiently large. We have a gradual input model: the burst does not arrive instantaneously. The server (i.e., the trunk) is allocated to customers in a FCFS fashion; once allocated to a customer, the server is deallocated only after the customer has fully arrived and has been fully served. Further, we assume that for the superposition traffic from all input lines the arrival epochs (arrival of the first bit) of the bursts form a Poisson stream.

If we consider the simplest ATM network comprising of a single ATM link between the multiplexer and demultiplexer, since burst level multiplexing is being done, as soon as the first bit of the burst is served at the multiplexer we can start playing the burst out at the receiving end, if we neglect the propagation delay. Thus the only delay incurred is the waiting time of the first bit of the burst after its arrival at the multiplexer, assuming zero propagation delay on ATM link. We obtain the distribution of this waiting time via level-crossing analysis [1, 16].

Let

λ = aggregate burst arrival rate on all the access links together

σ = line speed (bits / unit time)

τ = trunk speed (bits / unit time)

$c := \frac{\tau}{\sigma}$, & it is assumed that $c \geq 1$.

Let $n = 1, 2, 3, \ldots$ index the successive bursts in the composite input stream, the bursts being ordered by the arrival epochs $(t_1, t_2, \ldots)$ of the first bits of the bursts. With this indexing, for $n \geq 1$, define

B_n = time interval between the arrival epochs of the first and last bits of the n-th burst over the low speed line.

$\{B_n\}$ are i.i.d., and $B_n \sim$ Exponential (b^{-1}). We know that for a single-server FIFO queue with Poisson arrivals, limiting distributions for both customer waiting time and virtual waiting time are equal when they exist.

Let $\{W(t), t \geq 0\}$ denote the virtual waiting time process for the above queue, which means that $W(t)$ would be the waiting time for a burst to start getting service if its arrival were to occur at epoch t. $W(t)$ has right continuous sample paths, decreases at a unit rate between the jumps at the arrival epochs. Consider the n-th burst that starts arriving at t_n. If the service of the burst begins more than B_n/c time units before it finishes arriving, then its transmission over the trunk will complete at the same instant that it finishes arriving over the line. Such a situation will occur if $B_n - W(t_n-) \geq B_n/c$. In this case there will be a jump in $W(t)$ of an amount $B_n - W(t_n-)$. The server has to remain idle while waiting for the subsequent bits of the burst to accumulate in the buffer. If on the other hand $B_n - W(t_n-) < B_n/c$, then the trunk cannot finish serving the burst before it finishes arriving. In this case the jump in $W(t)$ will be of size B_n/c. It follows that

$$\begin{aligned} W(t_n) &= W(t_n-) + \max((B_n - W(t_n-)), B_n/c) \\ i.e., &\qquad W(t_n) = \max(B_n, W(t_n-) + B_n/c) \end{aligned}$$

Since $\{B_n\}$ are i.i.d. and we have assumed that the superposition burst arrival process is Poisson, $\{W(t)\}$ is a Markov Process. Recall that at light loads, because of the gradual input, the server is not work-conserving and the mean of the effective burst service time is greater than b/c where b is the mean transmission time of a burst over the low speed line. However, at heavy load, the mean of the effective burst service time approaches the limiting value b/c. Thus, it is clear that the queue will be stable if $\lambda b/c < 1$, $\lambda b/c =: \rho$ is the trunk utilization.

Consider the stationary distribution of $\{W(t)\}$ and denote the density of its continuous part by $w(x), x > 0$, and let w_0 denote the point mass at 0. Let W denotes the corresponding stationary random variable. From a theorem due to Brill and Posner [1], the long run average rate of down crossings of level $x > 0$ is equal to $w(x)$, with probability 1. Balancing the long run average rate of down crossings with that of upcrossings of level $x > 0$ results in the equation

$$\begin{aligned} w(x) &= \lambda w_0 Pr\text{ (upcrossing } x/W = 0) \\ &+ \lambda \int_0^x Pr\text{ (upcrossing } x/W = u) w(u) du\ , \qquad x > 0 \end{aligned} \tag{1}$$

Let B denote a random variable with the common distribution of $\{B_n\}$. Since B is exponentially distributed with mean b, we have

$$Pr\text{ (upcrossing } x/W = 0) \;=\; e^{-x/b} \tag{2}$$

Consider

$$\begin{aligned} &Pr(\text{upcrossing} x/W = u) \\ &= Pr(\max(B, u + \frac{B}{c}) > x) \\ &= Pr(\max(B, u + \frac{B}{c}) > x, B - u \geq \frac{B}{c}) \\ &+ Pr(\max(B, u + \frac{B}{c}) > x, B - u < \frac{B}{c}) \\ &= Pr(B > x, B \geq \frac{cu}{c-1}) + Pr(B > c(x-u), B < \frac{cu}{c-1}) \end{aligned} \tag{3}$$

Substituting Equations (2) and (3) in Equation 1, we get

$$\begin{aligned} w(x) &= \lambda w_0 e^{-x/b} + \lambda \int_0^x Pr(B > x, B \geq \frac{cu}{c-1}) w(u) du \\ &+ \lambda \int_0^x Pr\left(B > c(x-u), B < \frac{cu}{c-1}\right) w(u) du \end{aligned}$$

Simplifying,

$$\begin{aligned} w(x) &= \lambda w_0 e^{-x/b} + \lambda \int_0^{x(1-1/c)} e^{-x/b} w(u) du \\ &+ \lambda \int_{x(1-1/c)}^x e^{-c(x-u)/b} \ \ w(u) du \ , \qquad x > 0 \end{aligned}$$

Also we have the normalizing condition,

$$w_0 + \int_{0+}^{\infty} w(u) du = 1$$

With $f(x) \stackrel{\Delta}{=} w(x)/w_0$, the above two equations reduce to the following forms

$$\begin{aligned} f(x) &= \lambda e^{-x/b} + \lambda \int_0^{x(1-1/c)} e^{-x/b} \ f(u) du \\ &+ \lambda \int_{x(1-1/c)}^x e^{-c(x-u)/b} \ \ f(u) du \ , \qquad x > 0 \qquad (4) \\ w_0^{-1} &= 1 + \int_{0+}^{\infty} f(u) du \qquad (5) \end{aligned}$$

Now note that Equation 4 is a *Volterra integral equation* of the second kind which has the general form [19, Sect. 1.3]

$$f(x) - \lambda \int_0^x K(x,y) f(y) dy = \phi(x)$$

where the function $K(x,y)$ is the kernel of the integral equation and $\phi(x)$ is called the forcing function. In Equation 4,

$$\begin{aligned} \phi(x) &= \lambda e^{-x/b} \ , \text{ and} \\ K(x,y) &= \begin{cases} e^{-x/b} & ; \ \ 0 \leq y < x(1-1/c) \\ e^{-c(x-y)/b} & ; \ \ x(1-1/c) \leq y < x \end{cases} \end{aligned}$$

We used numerical methods [10, 11, 6] to solve the above equations and to obtain EW [12].

3.3 Comparison with Simulation Results

We performed a simulation of the actual discrete-time model to test the validity of the fluid flow approximation and the Poisson assumption for the superposition burst arrival

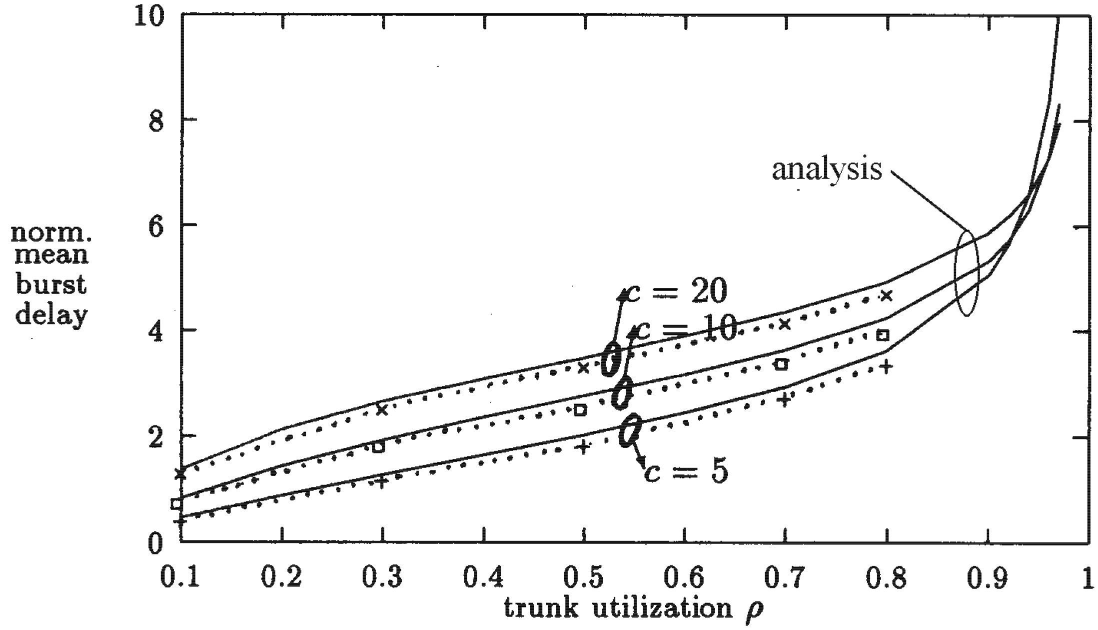

Figure 4: Comparison of analysis (solid curves) and simulation for burst level multiplexing; curves are parameterised by the trunk speed to line speed ratio c; $M = 20$ for simulation.

process. We simulated a single server queue with M inputs, each input carrying independent bursty traffic characterized by alternating bursts and silences both geometrically distributed. These inputs are assumed to be slotted synchronous lines. Because of the synchronous slot structure, it is possible that the leading cells of more than one burst arrive simultaneously. In such cases one burst is randomly chosen for service, and its cells are served successively without interruption.

Normalized mean waiting time (normalized with respect to the average burst transmission time on the low speed line) as a function of the trunk utilization ρ is shown in Figure 4. The continuous curves are the results of analysis; curves for different values of trunk speed to line speed ratio c are shown. Except at very high trunk utilizations, the mean delay increases with c. The trunk utilization $\rho(= \lambda b/c)$ is the fraction of time the server (trunk) does useful work, and it is not the fraction of time the trunk is allocated to transmit a burst; the latter includes the idle time due to the gradual arrival of the burst, in addition to the useful work. Thus with higher value of c (slower access line speed), to keep the trunk utilization same, the burst arrival rate λ is to be increased and hence the increase in mean delay with c. At very high trunk utilization, the system behavior is governed by the increased service rate due to faster trunk speed.

The corresponding curves due to simulation are shown by symbolic curves. We observe that the fluid flow approximation is reasonably accurate with average burst length of 20 cells and, though the Poisson assumption gives conservatively larger delays, with $M \geq 20$ the simulation curves are close to the analytical curves.

3.4 Comparison of The Two Multiplexing Strategies

In the interleaving case (round-robin scheme) we cannot start playing out the burst at the receiving end as soon as the leading cell becomes available, unlike the burst level multiplexing scheme. The first cell of a burst is delayed (buffered) until a predefined delay threshold (playout delay) is reached. Then, if the delay variation is within specified requirements, the buffer is able to deliver a continuous burst, without any interruption. Thus the end-to-end delay is the sum of the waiting time of the first cell (X_1), the transmission time of this cell, and the fixed playout delay. We assume 99.9 percentile of the burst expansion ϵ (denoted by $\epsilon_{99.9}$) as the playout delay [12]. Through discrete time simulation we obtain the distributions of X_1 and ϵ since direct stochastic analysis is found to be intractable.

Figure 5 shows the mean end-to-end delay of a burst with the two multiplexing strategies. For $c \leq 3$, burst level multiplexing has an advantage over cell level multiplexing for all values of the trunk utilization ρ (fraction of time the server (trunk) does useful work). Note that, if the access lines are of 45 Mbps and the ATM link is of 150 Mbps then $c \doteq 3$. For $c = 4$, again burst level multiplexing has an advantage except for low values of ρ. When $c \geq 5$, the burst level multiplexing scheme is not preferable at all.

When we consider the *worst case*, e.g., 99.9 percentile of the end-to-end delay [12] then, for $c = 2$, burst level multiplexing has an advantage over the round-robin scheme for trunk utilization exceeding 0.5. When $c = 3$, burst level multiplexing still has an advantage in the heavy traffic region. With trunk speed to line speed ratio > 3, the round-robin scheme is better.

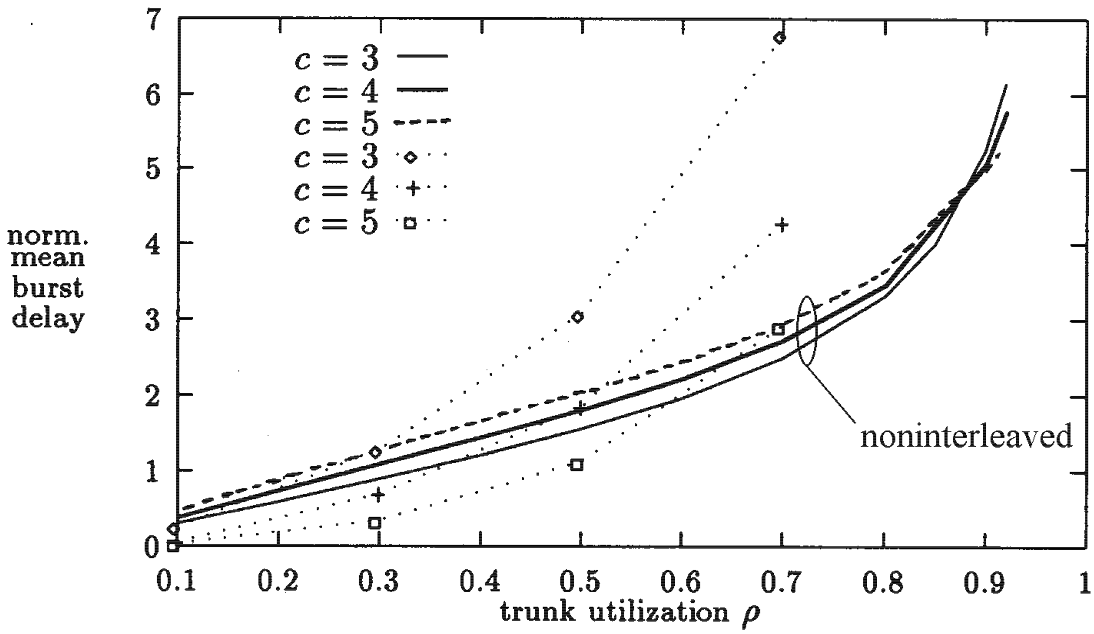

Figure 5: Normalized mean burst delay, i.e., mean delay between burst arrival at ingress point and play out initiation at egress point, normalized w.r.t. average burst transmission time over the access line, for the two different multiplexing strategies

4 End-to-End Performance of a Hub Based ATM Network

In this section we examine whether the results described in Section 2, for the simple Markovian traffic model at the ATM switch, hold with more "realistic" traffic. We consider the combined effect of cell scheduling strategies for service at the multiplexer and at the ATM switch, and present an end-to-end delay performance study of a simple ATM network which consists of a single ATM cell switching node connected to sources via statistical multiplexers, as shown in Figure 1. Clearly, queueing analysis of the switch with the true statistical model for the multiplexer output traffic in either multiplexing scheme is intractable; hence we have resorted to a detailed simulation.

4.1 Simulation Model

We consider a scenario in which two types of services are being supported by the simple ATM network, namely VBR video and traffic from campus networks. The cellizer associated with a VBR video codec is assumed to output alternating bursts of consecutive cells and silences; a geometric number of cells (with mean $(1-p_2)^{-1}$) during a burst, and a geometric number of idle slots (with mean $(1-q_2)^{-1}$) during a silence. A number of such cellizer outputs are connected through low speed access lines via a multiplexer to a high speed link, which terminates at an ATM switch port.

Traffic from campus networks will carry interactive services, e.g., interactive simulations with an image on a graphics workstation in one location being constantly updated by a program running on a supercomputer in a different location. Such traffic will have short bursts but will be delay sensitive. This less bursty traffic is also assumed to alternate between bursts and silences, both geometrically distributed. The mean burst length is $(1-p_1)^{-1}$, with $p_1 < p_2$. A number of these traffic streams are multiplexed onto a high speed link connected to an ATM switch port. We use the terms type 1 traffic and type 2 traffic, respectively, for traffic from the campus networks and VBR video traffic. We assume that a fraction α of the switch inputs have multiplexed traffic from type 1 sources and the remaining inputs have multiplexed traffic from type 2 sources.

Since we are interested in quantifying the combined effect of cell scheduling strategies for service at the multiplexer and at the switch, we study the four schemes listed below:

NON-PS: Noninterleaving strategy (burst level multiplexing) is used in all multiplexers, and SEBF priority selection is used to resolve the output conflict at the ATM switch (i.e., irrespective of the strategy used at the multiplexers, at the switch we always give priority to the inputs carrying multiplexed traffic from type 1 sources)

NON-RS: Noninterleaving strategy is used in all multiplexers, and random selection is used to resolve the output conflict at the ATM switch.

INT-PS: Interleaving strategy (round-robin cell level multiplexing) is used in all multiplexers, and SEBF priority selection is used to resolve the output conflict at the ATM switch.

INT-RS: Interleaving strategy is used in all multiplexers, and random selection is used to resolve the output conflict at the ATM switch.

Note that we do not consider the LEBF policy at the switch as our earlier analysis has already shown that it yields very poor performance.

We are interested in the *end-to-end* delay performance (i.e., delay from the beginning of arrival at the ingress point until playout initiation at the egress point) of a burst in the network for either type of traffic. We have already mentioned the importance of retaining the cells within a burst together, and hence the need for a playout delay to be enforced at the demultiplexer when we have the interleaving strategy at the multiplexer. Note that, even when the noninterleaving strategy is used at the multiplexer, cells from different bursts may get interleaved while being switched. We set the playout delay equal to the 99.9 percentile of the random variable ϵ defined in Section 3.1; denote this delay by $\epsilon_{99.9}$. Thus if W_0 denotes the time from the arrival of the leading cell of a burst at the multiplexer at the ingress point, until it reaches the playout buffer at the egress point, then the end-to-end delay is $W_0 + \epsilon_{99.9}$. For traffic of each type (i.e., 1 and 2), the mean of W_0 and the 99.9 percentile of ϵ are obtained from the simulation. The sum of these two, for each traffic type, yields the mean end-to-end burst delay.

4.2 Simulation Results

The mean burst delays for each type of traffic, normalized with respect to the mean burst transmission time over the access line, are listed in Table 1, for the various schemes described above for the following set of parameters:

- Number of inputs to each multiplexer = 10
- Number of inputs to the switch = 8
- Trunk speed to access line speed ratio for all multiplexers = 3
- Fraction of the switch inputs carrying multiplexed traffic from type 1 sources (α) = 0.5
- Mean burst length for type 1 traffic = 1/0.9 cells (i.e., $p_1 = 0.1$)

scheme	*mean delay* $\rho_1 = 0.5,\ \rho_2 = 0.2$ *type 1*	*type 2*	*mean delay* $\rho_1 = 0.5,\ \rho_2 = 0.3$ *type 1*	*type 2*
non-ps	1.364	1.668	1.364	2.431
non-rs	2.256	1.485	2.861	2.142
int-ps	2.711	2.572	2.711	3.937
int-rs	3.506	2.050	3.958	3.283

Table 1: Comparison of mean end-to-end delay of a burst with ATM trunk to access line speed ratio =3 for both type 1 and type 2 sources (normalized w.r.t. the mean burst transmission time over the access line).

- Mean burst length for type 2 traffic = 20 cells (i.e., $p_2 = 0.95$)

We denote by ρ_1 (resp. ρ_2), the utilization of each ATM trunk into which type 1 (resp. type 2) traffic are multiplexed. The values of ρ_1 and ρ_2, chosen to keep the multiplexer queues and the switch input queues stable (see [13]), are specified in the table. Comparing the first and the third rows, and the second and the fourth rows, of Table 1, we observe that with the chosen value of 3 for the trunk speed to access line speed ratio, the mean end-to-end burst delay is less with noninterleaving than with interleaving for both type 1 and type 2, for either SEBF or RS. Further, for the noninterleaving multiplexing scheme, with SEBF priority selection the mean delay for type 1 is much lower than it is with RS. This improvement in type 1 mean delay with SEBF is at the expense of a small degradation in the mean delay of type 2 bursts. Thus, for the scenarios in Table 1, with mean end-to-end burst delay as the criterion, we conclude that the most desirable scheme is noninterleaving multiplexing combined with SEBF output contention resolution at the ATM switch. Observe that this is in agreement with the results of our analyses in Section 2 and Section 3.

With distribution VBR video, the successive bursts on the access line may belong to the same call/connection and the delay variability of the burst is also an important performance measure. To take into account the delay variation of the bursts, we compare the worst case delay performance by computing the 99.9 percentile of the end-to-end delay of a burst (i.e., (99.9 percentile of W_0) $+\epsilon_{99.9}$). The simulation parameters are the same as listed above. The normalized delays with various schemes are listed in Table 2. We find that again for each multiplexing scheme, SEBF yields much smaller delays for type 1, with a relatively

	99.9 percentile of end-to-end delay $\rho_1 = 0.5,\ \rho_2 = 0.2$		*99.9 percentile of end-to-end delay* $\rho_1 = 0.5,\ \rho_2 = 0.3$	
scheme	*type 1*	*type 2*	*type 1*	*type 2*
non-ps	4.2	8.12	4.2	10.46
non-rs	12.1	7.87	18.3	10.05
int-ps	4.8	4.79	4.8	8.40
int-rs	10.8	3.83	13.8	6.92

Table 2: Comparison of 99.9 percentile of end-to-end delay with trunk speed to line speed ratio = 3 for both type 1 and type 2 sources (normalized w.r.t. burst transmission time over the access line).

small increase in type 2 delays. With the SEBF scheme at the ATM switch, *interleaved* multiplexing is the better policy as it yields much lower delays for type 2, with only a small increase in type 1 delay owing to stretching of type 1 bursts. Thus, with 99.9 percentile of the end-to-end burst delay as the criterion, the most desirable scheme is interleaved multiplexing combined with SEBF contention resolution at the ATM switch. This is again in agreement with the results of our analyses presented in Section 2 and Section 3.

The type 1 traffic can be from campus area networks with much lower access line speed than the ATM link speed (e.g., the access line speed of 1.5 Mbps for the type 1 traffic and 45 Mbps for the type 2 traffic, and the ATM link speed of 150 Mbps). Motivated by this scenario we simulated the ATM network of Figure 1 with different trunk speed to access line speed ratios for the access multiplexers multiplexing type 1 and type 2 sources. Normalized mean end-to-end delay of a burst for the various schemes are listed in Table 3, for the access line to trunk speed ratio of 30 for type 1 sources and a ratio of 3 for type 2 sources. In this case it is obvious that the interleaving is advantageous for type 1 because of the large speed ratio. So in the simulations we always have interleaving for type 1 and noninterleaving or interleaving for type 2.

Thus in Table 3 we have the same values for type 1 with NON-PS and INT-PS. However, the mean delay for the type 1 with NON-RS is more compared to that with INT-RS. This is because of the fact that with noninterleaving for type 2 traffic, it will be more bursty (serial correlation of the output link demands will be more) at the switch inputs; and with random selection policy for the output conflict resolution, this larger burstiness of type

scheme	*mean delay* $\rho_1 = 0.5,\ \rho_2 = 0.3$ *type 1*	*type 2*	*mean delay* $\rho_1 = 0.5,\ \rho_2 = 0.35$ *type 1*	*type 2*
non-ps	0.7205	1.717	0.7205	2.099
non-rs	0.9124	1.687	0.9538	2.043
int-ps	0.7205	3.125	0.7205	4.014
int-rs	0.8438	2.654	0.881	3.380

Table 3: Comparison of Mean end-to-end delay with trunk to line speed ratio = 30 (resp. = 3) for type 1 (resp. for type 2) sources (normalized w.r.t. burst transmission time over the access line)

2 will increase the delay experienced by type 1 cells. For type 2 traffic, mean burst delay is much less with noninterleaving than with interleaving. Further, with NON-PS mean burst delay for type 1 is better than with NON-RS, with a slight increase in mean burst delay for type 2. Thus, again we find that for mean end-to-end burst delay, the most desirable combination is noninterleaved multiplexing of type 2 sources, and SEBF output contention resolution at the ATM switch.

5 Conclusion

In this paper we studied the combined effect of cell scheduling strategies at the access multiplexer and at the ATM switch, on the end-to-end delay performance of two class bursty traffic, in a hub based ATM network. We gave, in two separate sections (Section 2 and Section 3), the summary of the results of analytical studies of these strategies with the switch and the multiplexer in isolation (for the complete analyses see [12], [13], and [14]). Then we presented a simulation study of end-to-end burst delays in an ATM network with an input queueing cell switching hub, and customer access lines being multiplexed into the input link of this hub. Each access multiplexer is fed by on/off sources. Some multiplexers are fed by sources with long bursts (i.e., VBR communication or distribution video), and others by sources with short bursts (i.e., traffic from campus networks).

We find that, although no assumptions were made about the output processes of the multiplexers feeding into the ATM switch in the hub network, the simulation study confirms what may have been expected from the analysis of the multiplexer and the switch in isolation. Note that the analytical study of the switch was made with an analytically tractable Markovian input model. In particular, we find that, there is a threshold for the ATM link to customer access line speed ratio (3 for the models we have studied), such that, at or below this ratio, for the more bursty traffic the most desirable end-to-end mean burst delay performance occurs when we have burst level (i.e., noninterleaved) multiplexing at the access multiplexer, and SEBF priority policy at the switching hub. However, when we compare the worst case delay performance, i.e., the 99.9 percentile of the end-to-end delay of a burst, we find that the combination of round-robin scheme for the access multiplexer and SEBF priority selection for the ATM switch perform best. The mean end-to-end burst delay can be a good measure when the successive bursts on an access line are unrelated (e.g., an image database server sending successive still image frames). However, with distribution video like HDTV, the successive bursts on the access line may belong to the same call, and the burst delay variability is also an important measure.

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