Jitter At An ATM Multiplexer In The Presence Of Correlated Traffic

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Abstract

This paper discusses the traffic distortion suffered by a periodic source at an ATM multiplexer, in the presence of interfering ON-OFF sources. We analyze a FIFO queue that serves the superposition of the periodic source and background traffic to obtain the jitter density. Traffic distortion is not limited to periodic sources alone. We relax the requirement of periodicity and investigate the jitter of any arbitrary renewal traffic stream. We observe that the jitter is very sensitive to the number of ON-OFF sources in addition to the variability of each source. We show that cells belonging to the periodic source cluster together for high values of the mean burst duration of the interfering ON-OFF sources. This distortion in traffic characteristics manifests in increased bandwidth requirements at the latter multiplexing stages of the connection. We also show that the departure distribution of any arbitrary renewal arrival process bears little resemblance to the original arrival distribution in the presence of highly bursty background traffic streams. It is clear that while statistical multiplexing enables efficient and cost-effective transport, jitter control at the intermediate switching points is necessary for guaranteeing the QOS requirements of real-time traffic.

1 Introduction

High speed networks are expected to support a variety of multimedia services such as voice, video, image and facsimile besides data. ATM (Asynchronous Transfer Mode) is being adopted as the transport and multiplexing technique to provide such diverse applications in an integrated services network.

Statistical multiplexing is the key to the financial success of ATM, with traffic generated from different sources statistically multiplexed over high speed ATM links. Consequently, variable size packets are segmented into constant size 'cells' (48 bytes of payload information and 5 bytes of header) before being admitted into the network. This constant unit of transmission implies that ATM networks can be analyzed as slotted time systems with one cell of information transmitted in every slot.

An adverse effect of statistical multiplexing is to distort the traffic characteristics of sources as they transit through ATM switches/multiplexers (MUX). This might have a severe impact on the Quality of Service (QOS) delivered by the network to the connection in question. Constant Bit Rate (CBR) traffic (which generates cells on a periodic basis) is expected to be one of the chief constituents of future broadband traffic. CBR traffic is typically generated by video and imaging applications. These applications generate packets that are segmented into cells at a constant rate, resulting in periodic cell arrivals. Compressed video usually generates cells at a variable rate but a traffic shaper is usually employed to space cells such that the resulting traffic stream into the network forms a periodic process. This facilitates a more efficient usage of network bandwidth because this modified traffic stream is less bursty.

An important performance measure for periodic traffic is the cell jitter defined as the distortion of the periodic nature of the cell arrival stream at multiplexing stages of the network [4]. This distortion is not limited to periodic sources alone. For instance, the traffic characteristics of ON-OFF sources are modified as the traffic stream is multiplexed through several ATM switches. In transporting real-time video or voice, bounds on absolute delay for cells are not the only significant criterion; jitter should also be controlled. This variance in inter-cell gaps affects quality only if the receiver does not have adequate memory to smooth out the jitter before playing it back at the destination. The low cost of memory devices imply that receivers can possess sufficient memory to smooth out inter-cell gaps for a burst of cells. However, for real-time applications, the original data stream has to be faithfully recreated at the receiver after a fixed delay offset. Cells with shorter delay have to wait in the receiver's buffer in order for the cells with longer delay to arrive before they can be played out. Thus, the synchronization process is determined by the tail of the delay distribution.

Traffic distortion, caused by jitter, also has a significant impact on the admission control protocols employed by the network. A new call is admitted into the network based on the current network state and the impact of the call, if admitted, on the QOS of the connections already being transported by the network. The requested bandwidth (or *effective* bandwidth) if available, is reserved at every switching node in the new connection's path to its destination. If the variability of the traffic characteristics is diminished as a result of several multiplexing stages, such an admission control policy leads to an overcontrolled network implying a less effective usage of network resources. On the other hand, an increased variability would adversely affect the performance of other users. It has already been pointed out in [3] that as cells of a connection proceed to the destination node, they tend to cluster together forming longer bursts and thereby cause congestion at the intermediate nodes.

It should be pointed out that jitter can be controlled if the switches/multiplexers employ either a round robin or a fair queueing service discipline in place of the familiar FIFO service philosophy. This aspect has been discussed in [5]. Although experimental testbeds are implementing Fair Queueing (FQ) switches [2], consensus is yet to be reached on the proper choice of service philosophy. Moving functions to the edge of the network to reduce the cell-processing time as much as possible is ATM's governing principle, but, round-robin service scheduling policies have the opposite effect and these schemes do not scale well with the number of sessions. Moreover, it is not reasonable to assume that FQ switches will completely replace the FIFO variety.

Wang and Crowcroft analyze burstiness and jitter using a deterministic model in [9]. The jitter of a cell in a synchronization unit is defined with respect to the delay experienced by the first cell in the unit. A synchronization unit is defined as a group of cells that share a common fixed delay offset[1].They also determine upper bounds for jitter. However, they do not consider multiplexing of sources which is the principal reason for cell delay variation in ATM networks.

In this paper, we adopt a stochastic model to compute jitter in the presence of interfering

[1]The delay offset represents the estimated upper bound of delay a cell may experience.

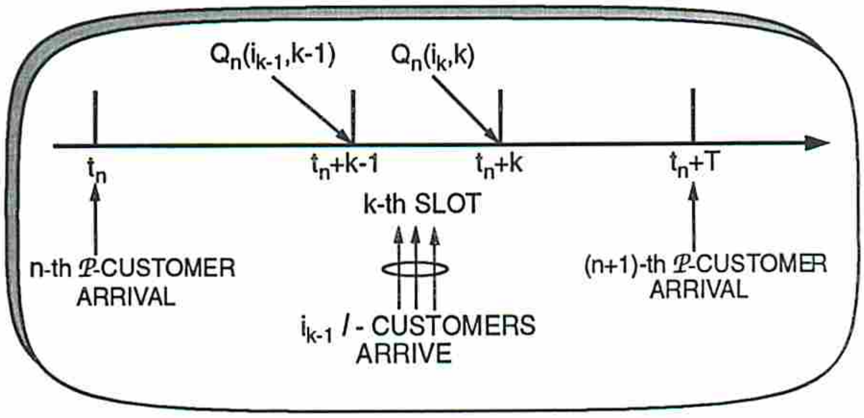

Figure 2: Evolution of the random variables.

interested in relating the queue size prior to the $(n+1)$th $\mathcal{P}$-customer arrival instant to that of the nth $\mathcal{P}$-customer arrival instant. Let $Q_n(i_k, k)$, $0 \leq k \leq T$, denote the total number of cells waiting in the queue, (excluding the one in service) just prior to the $(t_n + k)$-th slot[4] given that the number of interfering sources in the ON state is i_k in that slot. For example, $Q_n(i_0, 0)$ defines the queue length immediately before the n-th cell arrival from the periodic stream. We assume the following sequence of event occurrences in our analysis:

- Cells arrive at slot boundaries.
- Each interfering ON-OFF source could possibly change from active (silent) to silent (active) mode.
- A cell (if queued in the buffer) is transmitted on the outgoing link.

A cell arriving at the beginning of the slot is served immediately if it encounters an empty queue. Figure 2 illustrates the evolution of the random variables. The following state equations can be written down:

$$Q_n(i_1, 1) = \sum_{i_0=0}^{N} p(i_0, i_1) \max(Q_n(i_0, 0) + i_0 + 1 - 1, 0) \quad 0 \leq i_1 \leq N \tag{4}$$

$$= \sum_{i_0=0}^{N} p(i_0, i_1)(Q_n(i_0, 0) + i_0)$$

$$Q_n(i_k, k) = \sum_{i_{k-1}=0}^{N} p(i_{k-1}, i_k) \max(Q_n(i_{k-1}, k-1) + i_{k-1} + 0 - 1, 0) \quad 0 \leq i_k \leq N \tag{5}$$

[4]i.e., just prior to the k-th slot following the arrival of the n-th $\mathcal{P}$-customer, $n = 1, 2, \cdots$.

where $p(m,n)$ is the probability that there are n ON-OFF sources in the active state at the beginning of the k-th slot given that the number of sources in the ON state at the beginning of the $(k-1)$-th slot is m, and is given by

$$p(m,n) = \sum_{i=0}^{m} \binom{m}{i} \alpha^i (1-\alpha)^{m-i} \binom{N-m}{n-i} (1-\beta)^{n-i} \beta^{N-m-(n-i)}, \quad (6)$$

$$0 \le i \le m, 0 \le n-i \le N-m$$

where $\binom{m}{i} \alpha^i (1-\alpha)^{m-i}$ is the probability that i among m active sources remain in the ON state and the remaining $(m-i)$ active sources make a transition to the OFF state in $[\,(k-1)T,\ kT)$. Similarly, the probability that $(m-i)$ among $(N-m)$ sources make a transition from the OFF state to the ON state is given by $\binom{N-m}{n-i} (1-\beta)^{n-i} \beta^{N-m-(n-i)}$. The "+1" in (4) and "+0" in (5) account for the $\mathcal{P}$-customers that arrive in slot $t_n + k$, $0 \le k \le T-1$.

Let $Q^*_{n,i_k,k}(z)$ denote the z-transform of $Q_n(i_k, k)$. Let $\pi_{n,k}(0) = \Pr\,[Q_n(0,k) = 0]$. It follows from (4) and (5) that

$$Q^*_{n,i_1,1}(z) = \sum_{j=0}^{N} z^j p(j, i_1) Q^*_{n,j,0}(z) \text{ and} \quad (7)$$

$$Q^*_{n,i_k,k}(z) = \sum_{j=0}^{N} z^{j-1} Q^*_{n,j,(k-1)}(z) + p(0,i_k) \cdot (1 - z^{-1}) \cdot \pi_{n,k-1}(0) \qquad 2 \le k \le T$$

Let $\mathbf{Q^*_{n,k}}(z)$ denote a column vector (of size $N+1$) of z-transforms with $Q^*_{n,j-1,k}(z)$ as its j-th element. Then the following equations are valid

$$\mathbf{Q^*_{n,1}}(z) = \mathbf{A_0}(z) \mathbf{Q^*_{n,0}}(z)$$

$$\mathbf{Q^*_{n,k}}(z) = \mathbf{A_1}(z) \mathbf{Q^*_{n,(k-1)}}(z) + \mathbf{B_{k-1}}(z) \qquad 2 \le k \le T$$

where $\mathbf{A_0}(z)$ and $\mathbf{A_1}(z)$ are both matrices of order $(N+1)$. The (i,j)-th elements of $\mathbf{A_0}(z)$ and $\mathbf{A_1}(z)$ are equal to $z^{j-1} p(j-1, i-1)$ and $z^{j-2} p(j-1, i-1)$ respectively. The vector $\mathbf{B_k}(z)$ can be written down as

$$\mathbf{B_k}(z) = (1 - z^{-1}) \cdot \pi_{n,k}(0) \cdot \mathbf{p_0} \qquad 1 \le k \le T-1$$

where $\mathbf{p_0}$ is a column vector with j-th element equal to $p(0, j-1)$. The recursion results in

$$\begin{aligned} \mathbf{Q^*_{n+1,0}}(z) &= \mathbf{Q^*_{n,T}}(z) \qquad (8) \\ &= \mathbf{A_1}^{T-1}(z) \cdot \mathbf{A_0}(z)\mathbf{Q^*_n}(z) + (\sum_{j=0}^{T-2} \mathbf{A_1}^j(z)\pi_{n,T-1-j}(0)) \cdot (1 - z^{-1}) \cdot \mathbf{p_0} \end{aligned}$$

where $\mathbf{A_1}^j(z)$ is the matrix $\mathbf{A_1}(z)$ multiplied j times and $\mathbf{A_1}^0(z)$ is the identity matrix I_{n+1}. The z-transform of $Q_n(k)$, the number of customers waiting in the queue (excluding the one in service) just prior to the $(t_n + k)$-th slot is given by

$$Q^*_{n,k}(z) = \sum_{j=0}^{N} Q^*_{n,j,k}(z) \qquad 1 \leq k \leq T$$

The recursion in (8) gives the z-transform of $Q_{n+1}(0)$ as a function of the z-transform of $Q_n(0)$, $n = 1, 2, \cdots$.

4.1 The steady state queue size

When the system reaches stationary state, $\mathbf{Q^*_n}(z) \to \mathbf{Q}^*(z)$, as $n \to \infty$, where $\mathbf{Q}^*(\cdot)$ denotes the z-transform of the steady state queue size just prior to the arrival instant of a $\mathcal{P}$-customer, not counting the one (if any) in service. Hence in the limit $n \to \infty$, (8) yields

$$\begin{aligned} [I_{n+1} - \mathbf{A_1}^{T-1}(z) \cdot \mathbf{A_0}(z)] \cdot \mathbf{Q}^*(z) &= (\sum_{j=0}^{T-2} \mathbf{A_1}^j(z)\pi_{T-1-j}(0)) \cdot (1 - z^{-1}) \cdot \mathbf{p_0} \\ \mathbf{Q}^*(z) &= [I_{n+1} - \mathbf{A_1}^{T-1}(z) \cdot \mathbf{A_0}(z)]^{-1}(\sum_{j=0}^{T-2} \mathbf{A_1}^j(z)\pi_{T-1-j}(0)) \cdot (1 - z^{-1}) \cdot \mathbf{p} \end{aligned}$$

where $\pi_k(0) = \lim \pi_{n,k}(0)$, as $n \to \infty$.

In order to determine $\mathbf{Q}^*(z)$, the unknowns $\pi_k(0)$, $k = 1, \cdots, T-1$, have to be determined. Define $Q^*_p(z) = \sum_{j=0}^{N} Q^*_j(z)$. Since $Q^*_p(z)$ (as the z-transform of a legitimate random variable), has to be analytic on the unit disk, the roots of the denominator of $Q^*_p(z)$ have to be "compensated" by the roots of the numerator of $Q^*_p(z)$. Stated otherwise, the numerator of $Q^*_p(z)$ has to vanish at the exact points where the denominator also vanishes. As in other instances, it can be shown using Rouche's theorem [8] that when the stability condition $\rho < 1$ holds, the denominator of $Q_p^*(z)$ has exactly $T-1$ roots on the unit disk $|z| \leq 1$. Of course, one of these roots has to equal unity[5]. The $T-1$ unknowns $\pi_k(0)$, $k = 1, \cdots, T-1$, can be computed by solving $T-2$ linear equations (excluding the root at unity) together with the identity $Q_p^*(1) = 1$. Since closed form expressions do not exist for $Q_p^*(z)$, we employ the software package *MATHEMATICA* which is capable of executing symbolic computations [10].

Our definition of the queue size Q taken together with the FIFO service discipline, implies that the z-transform of the waiting time (in steady state) of a $\mathcal{P}$-customer is also given by $Q_p^*(z)$.

4.2 Stationary Distribution of the Jitter

Let $Q_2^*(z_1, z_2)$ denote the steady state joint z-transform of the queue size prior to the arrivals of two consecutive $\mathcal{P}$-customers. Without loss of generality, we denote the queue sizes as Q_1 and Q_2 respectively.

$$\begin{aligned} Q_2^*(z_1, z_2) = E(z_1^{Q_1} z_2^{Q_2}) &= \sum_{k'=0}^{\infty} \sum_{k=0}^{\infty} z_1^k \, \text{Pr } (Q_2 = k' | Q_1 = k) \text{Pr } (Q_1 = k) z_2^{k'} \qquad (9) \\ &= \sum_{k=0}^{\infty} z_1^k \, Q_p^*(z_2 | Q_1 = k) \, \text{Pr } (Q_1 = k) \end{aligned}$$

Further,

$$Q_p^*(z_2 | Q_1 = k) = \sum_{j=0}^{N} Q_p^*(z_2 | Q_1 = k, \mathcal{A} = j) \, \text{Pr } (\mathcal{A} = j)$$

Now if the event $\{Q_1 = k, \mathcal{A} = j\}$ is true, then $Q_j^*(z) = z^k$, $k = 0, 1, \cdots$, which is the j-th element of the column vector $\mathbf{Q}^*(z)$. Let us denote

$$\pi_k(0; i) = \text{Pr } (Q_n(0, k) = 0 | Q_n = i)$$

It is clear that $\pi_k(0; i) = 0$ for $1 \leq k \leq \min(i, T-1)$ and $i = 1, 2, \cdots$.

Let $(B)_s$ denote the sum of the elements of the column vector $\mathbf{B}$. Then

[5] This "compensates" the term $(1 - z^{-1})$.

$Q_p^*(z_2|Q_1=k,\mathcal{A}=j)$ can be written down as $(\mathbf{Q}^*(z_2|Q_1=k,\mathcal{A}=j))_s$. From (8), we have

$$Q_p^*(z_2|Q_1=k,\mathcal{A}=j) = (\mathbf{A_1}^{T-1}(z_2)\mathbf{A_0}(z_2)\mathbf{e}_k)_s z_2^k + ((\sum_{m=0}^{T-2} \mathbf{A}_1^m(z_2)\pi_{T-1-m}(0;k))\cdot \mathbf{p_0})_s(1-z_2^{-1})$$

Let $\mathbf{A}'_k(z)$ and $\mathbf{C}_k(z)$ denote the vectors $\mathbf{A_1}^{T-1}(z)\cdot\mathbf{A_0}(z)\cdot\mathbf{e}_k$ and $((\sum_{j=0}^{T-2}\mathbf{A}_1^j(z)\pi_{T-1-m}(0;k))\cdot \mathbf{p_0})$ respectively. Let $\mathbf{e}_k$ be a unit column vector whose kth element is unity. $(\mathbf{A}'_k(z))_s$ denotes the sum of the elements of the kth column vector of the matrix $\mathbf{A_1}^{T-1}(z)\cdot\mathbf{A_0}(z)$. Also let $q_j = \Pr\ (\mathcal{A}=j)$. Substituting the above in (9), we have

$$\begin{aligned}
Q_2^*(z_1,z_2) &= \sum_{k=0}^{\infty} z_1^k\cdot \Pr\ (Q_1=k)\sum_{j=0}^{N} q_j\cdot((\mathbf{A}'_k(z_2))_s z_2^k + (\mathbf{C}_k(z_2))_s\cdot(1-z_2^{-1}))\\
&= \sum_{k=0}^{\infty}(z_1z_2)^k \Pr\ (Q_1=k)\sum_{j=0}^{N} q_j\cdot(\mathbf{A}'_k(z_2))_s + \sum_{k=0}^{T-2}\sum_{j=0}^{N} q_j\cdot(\mathbf{C}_k(z_2))_s \Pr\ (Q_1=k) z_1^k(1-z_2^{-1})\\
&= Q_p^*(z_1z_2)\sum_{j=0}^{N}(\mathbf{A}'_k(z_2))_s\cdot q_j + \sum_{k=0}^{T-2}\sum_{j=0}^{N}(\mathbf{C}_k(z_2))_s\cdot q_j\cdot \Pr\ (Q_1=k)z_1^k\cdot(1-z_2^{-1})
\end{aligned}$$

Notice that for the computation of $Q_2^*(\cdot,\cdot)$, only the first $T-1$ probabilities: $\Pr(Q_1=k), k=0,1,\cdots,T-2$, are required.

As $n\to\infty$ J_n tends to the random variable J. From (2), we have

$$J = Q_2 - Q_1.$$

Therefore, the z-transform $J^*(\cdot)$ of J is given by

$$\begin{aligned}
J^*(z) &= E(z^{Q_2-Q_1}) = E(z^{-Q_1}z^{Q_2}) = Q_2^*(\frac{1}{z},z) \qquad (10)\\
&= \sum_{j=0}^{N}(\mathbf{A}'_k(z))_s\cdot q_j + \sum_{k=0}^{T-2}\sum_{j=0}^{N}(\mathbf{C}_k(z))_s\cdot q_j\cdot \Pr\ (Q_1=k)z^{-k}\cdot(1-z^{-1})
\end{aligned}$$

The jitter J can take negative values implying that the z-transform in (10) is a two-sided transform. Notice that the range of $\bar{J}$ is the set $\{-T+1,-T+2,\cdots,-1,0,1,2,\cdots\}$. Multiplying (10) by z^{T-1} shifts the range of J to the non-negative integers, which could be inverted to yield the jitter density.

4.3 Distribution of Jitter for an Arbitrary Renewal Process

In this subsection, we relax the requirement of periodicity of the traffic stream in question and investigate the distortion incurred by any arbitrary renewal process. Renewal processes are characterised by independent identically distributed interarrival times. Define $a(k) =$ Prob [interarrival time $= k$ slots]. For the analysis to be tractable, we make the assumption that the interarrival time between cells from the renewal stream has finite maximum values, i.e., $\sum_{k=1}^{M} a(k) = 1$ where M is a finite integer. It is immediately apparent that the procedure used to obtain the distribution of the jitter for the periodic stream can be extended for the case of the renewal stream. Consequently, equation (8) can be rewritten as

$$\begin{aligned}\mathbf{Q}^*_{n+1}(z) &= \sum_{k=1}^{M} a(k)\mathbf{Q}^*_{\mathbf{n,k}}(z) \\ &= \sum_{k=1}^{M} \left\{ a(k) \cdot (\mathbf{A_1}^{k-1}(z) \cdot \mathbf{A}_0(z) \cdot \mathbf{Q}^*_n(z) + (\sum_{j=0}^{k-2} \mathbf{A}_1^j(z)\pi_{n,k-1-j}(0)) \cdot (1 - z^{-1}) \cdot \mathbf{p}_0) \right\}\end{aligned}$$

In steady state, $\lim_{n\to\infty} \mathbf{Q}^*_n(z) \to \mathbf{Q}^*(z)$ and $\mathbf{Q}^*(z)$ can be written as

$$\mathbf{Q}^*(z) = [I_{n+1} - \sum_{k=1}^{M} a(k) \cdot \mathbf{A}_1^{k-1}(z) \cdot \mathbf{A}_0(z)]^{-1} [\sum_{k=2}^{M} a(k) \cdot (\sum_{j=0}^{k-2} \mathbf{A}_1^j(z)\pi_{k-1-j}(0)) \cdot (1 - z^{-1}) \cdot \mathbf{p}_0)].$$

$Q^*_p(z)$ can be solved by following the same procedure outlined in the previous sections and the cell inter-departure distribution of the renewal arrival process can be obtained.

5 Numerical Results

We will investigate the effect of several parameters, such as the number, N, of interfering ON-OFF sources and the mean active period given by $1/(1-\alpha)$ of an ON-OFF source, on the jitter statistics of a periodic traffic stream. We limit our discussion to those periodic traffic sources with period $T = 5$, owing to the computational constraints imposed by *MATHEMATICA*.

Figure 3 illustrates the effect of the background traffic on the variance of the jitter, σ_J^2, for varying values of the mean active period of an ON-OFF source. For a given background

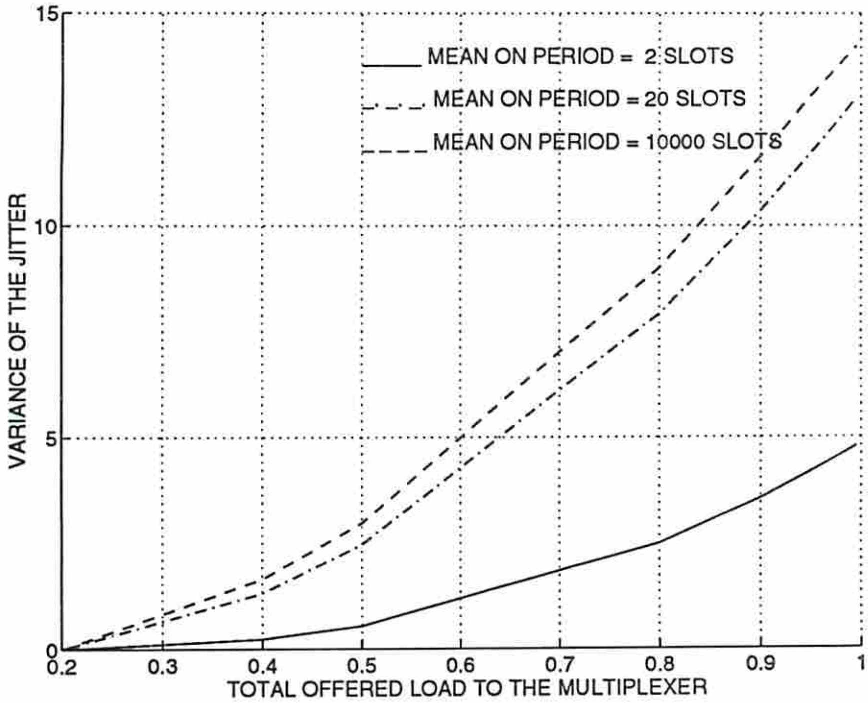

Figure 3: The variance of the jitter as a function of the background traffic.

traffic load, the variance of the number of arrivals in an active period of a single ON-OFF source is given by:

$$\frac{\alpha^2}{(1-\alpha)^2}$$

$\sigma_{\mathcal{J}}^2$ captures the distortion experienced by the periodic traffic due to its interaction with the background traffic. The average arrival rate of the N $\mathcal{I}$-customers is given by:

$$\lambda_i = \frac{N(1-\beta)}{2-\alpha-\beta}$$

In particular, Figure 3 depicts $\sigma_{\mathcal{J}}^2$, as a function of the total offered traffic to the multiplexer, for several values of α (and consequently, for several values of the mean active period of the ON-OFF source.). As expected, the variance of the jitter increases as the variability of the background traffic also increases. However, notice that $\sigma_{\mathcal{J}}^2$ converges to a finite value as $\rho \to 1$. As $\rho \to 1$ and the queue size Q starts to explode, $Pr(Q \leq M) \to 0$ for any $M < \infty$ and therefore, $\pi_k(0; i) \to 0$ for any $i < \infty$ and $1 \leq k \leq \min(i, T-1)$. Thus (10) can be

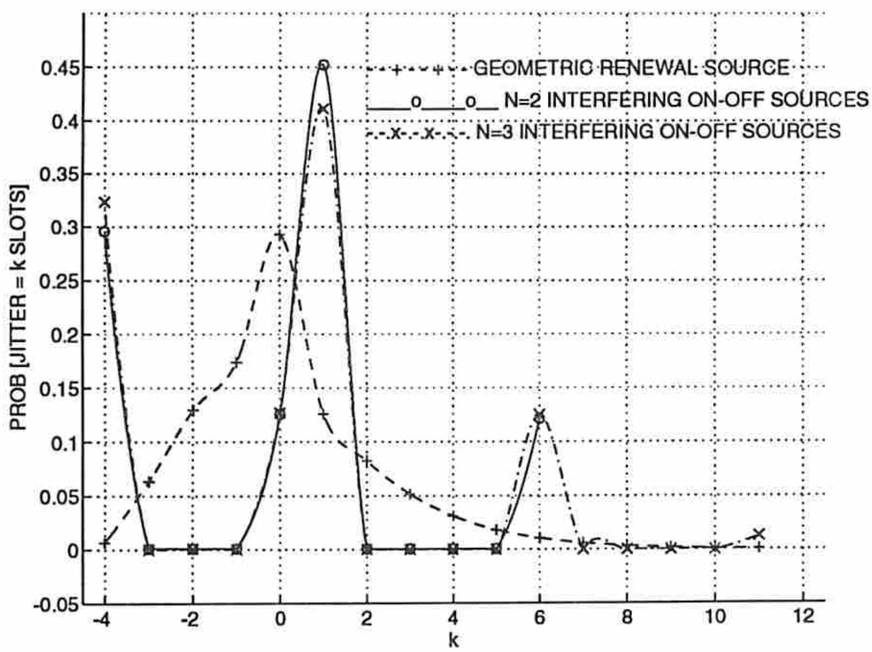

Figure 4: Jitter histogram of a periodic traffic stream ($T = 5$) in the presence of non-renewal and renewal traffic. The multiplexer utilization is set at 0.9.

rewritten as

$$J^*(z) \rightarrow \sum_{j=0}^{N} (\mathbf{A}(z) \cdot \mathbf{e}_{j+1})_s \cdot q_j$$

which implies σ_J^2 converges to a finite value as $\rho \rightarrow 1$.

Figure 4 depicts the histogram of the jitter for a periodic stream with period $T = 5$ when the total offered load to the multiplexer is 0.9. The discrete points in the plots have been joined to enhance their readability. The jitter distribution is plotted for two values of the number of interfering ON-OFF sources (N). We employed the following values for the mean active duration: 1000 and 10000 slots for $N = 2$ and $N = 3$ respectively. We chose such highly variable interfering sources to illustrate the degree of distortion of the periodic traffic. The distribution of the jitter for a geometric renewal interfering source is also shown for comparison [1]. For renewal background traffic, most of the mass of the jitter is concentrated around $J = 0$ for a relatively high queue utilization ($\rho = 0.9$.). However, it is immediately clear from the figure that the histogram of the jitter exhibits substantially different behavior for non-renewal traffic (viz., superposition of ON-OFF sources.). Both instances of non-renewal background traffic result in a high probability for the case where $J = -T + 1$, which corresponds to the case when the $\mathcal{P}$-customers depart back to back from

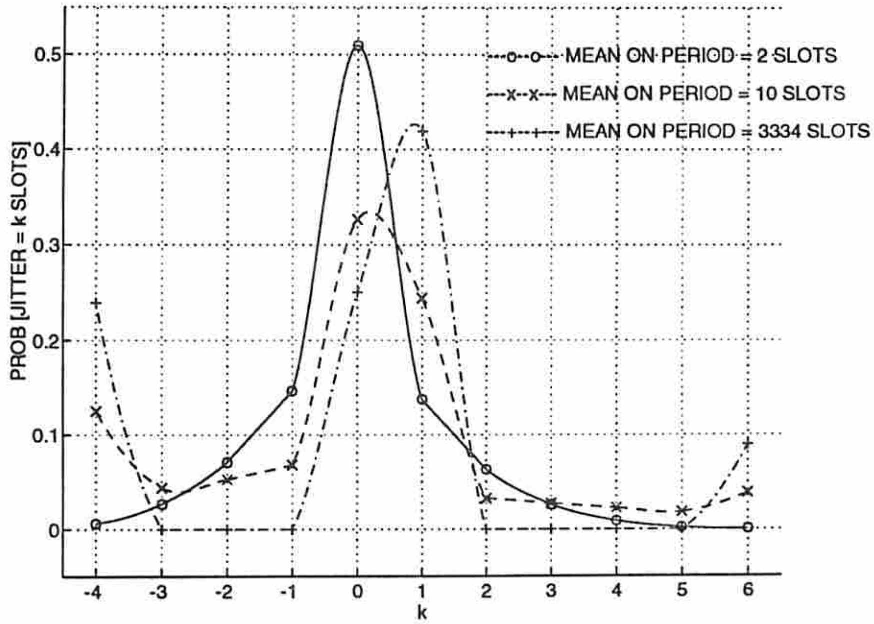

Figure 5: Jitter histogram for a periodic traffic ($T = 5$) plotted as a function of the burstiness of the background traffic.

the multiplexer ; recall, that the jitter is lower bounded by $-T + 1$. This observation can be explained as follows: When N=2, a mean active duration of 1000 slots corresponds to a mean idle duration of 1860 slots yielding a total offered load of 0.9. When both ON-OFF sources are idle, the $\mathcal{P}$-customers are served consecutively by the multiplexer resulting in their clustering. More generally, let n out of N ON-OFF sources be active during the T slots between two consecutive $\mathcal{P}$-customer arrivals. nT $\mathcal{I}$-cells would be generated during this period, $T - 1$ of which receive service. This implies that $nT - (T - 1)$ $\mathcal{I}$-cells would separate the two $\mathcal{P}$-customers. This explains the observed maxima at k = -4, 1, 6 and 11 for the case of $T = 5, N = 3$ and $n = 0, 1, 2$ and 3 respectively. It is apparent that the distortion experienced by the periodic source is dependent on the number of ON-OFF sources in addition to the variability of each source.

In Figure 5, the distribution of the jitter is plotted for a periodic source with period $T = 5$ in the presence of two interfering ON-OFF sources, for a multiplexer utilization of 0.9. When the variability of the background traffic is small, most of the mass of the jitter is concentrated around $J = 0$, similar to the case of renewal traffic. However, as the background traffic becomes more bursty, the likelihood of $\mathcal{P}$-customers departing back to back from the multiplexer increases significantly. This has a significant impact on the bandwidth requirements of the periodic traffic at the adjacent node in its path.

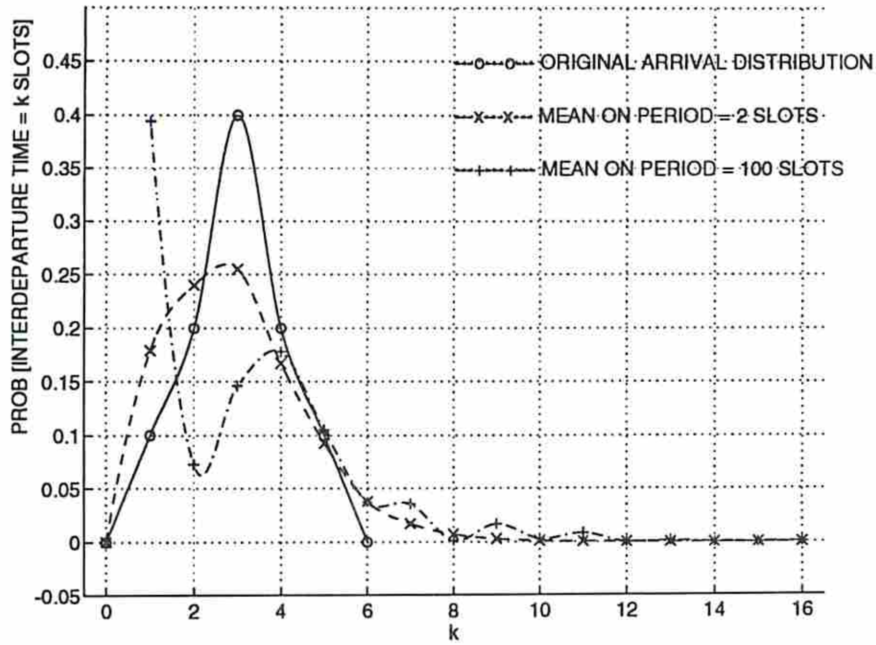

Figure 6: Interdeparture distribution of an arbitrary renewal traffic stream in the presence of non-renewal background traffic.

Traffic distortion of real time traffic can typically be prevented with the help of cell-level priorities. However, such distortion is not limited to periodic sources alone. We relax the requirement of periodicity and investigate the change in traffic characteristics of any arbitrary arrival process. Figure 6 illustrates the traffic distortion suffered by a renewal arrival process with the following interarrival parameters: $a(1) = 0.1$, $a(2) = 0.2$, $a(3) = 0.3$, $a(4) = 0.2$ and $a(5) = 0.1$. Recall that $a(k) =$ Prob[interarrival time $= k$ slots]. It is more appropriate to plot the interdeparture distribution which captures the distortion from the original arrival distribution. Our definition of jitter is more relevant for a periodic source. Superposition of three ON-OFF processes were considered such that the total offered load to the multiplexer is 0.9. As noted in the previous examples, the degree of distortion increases drastically with an increase in the burstiness of the interfering ON-OFF processes.

Figure 7 shows the effect of multiple hops on the jitter distribution. Background traffic is regenerated at each hop wherein the periodic source is multiplexed with a different set of background ON-OFF sources at each node, which make their exit after service. Simulations were used to compute the jitter density of a periodic source with $T = 5$ slots which traverses three hops in the presence of interfering traffic. Jitter is upper bounded by $NT - (T - 1)$ at the departure point of a single multiplexer. Given that there are N background ON-OFF

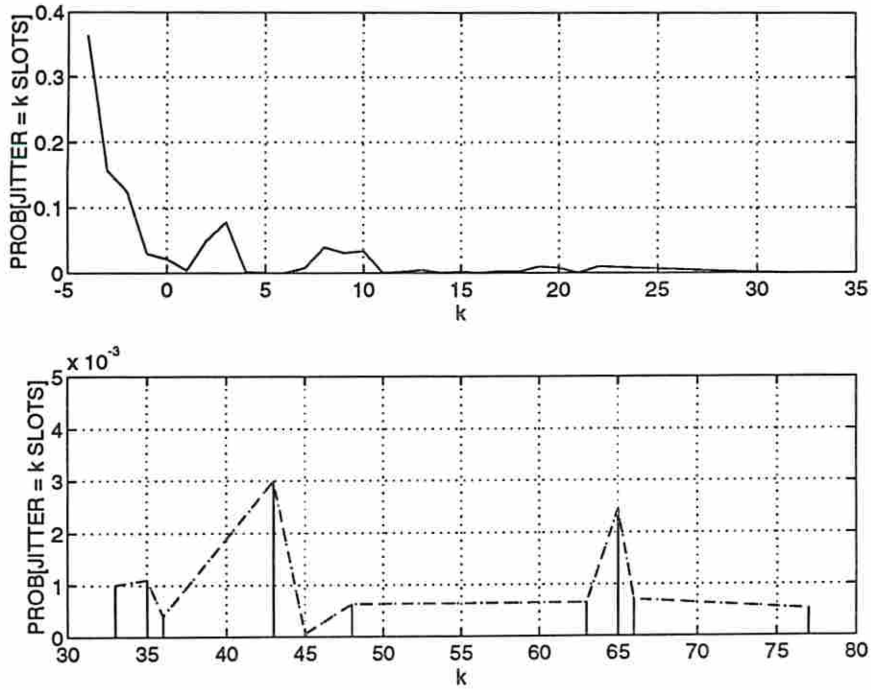

Figure 7: Effect of three hops on the evolution of the jitter distribution of the periodic source. The link utilizations in the multiple hop model are set at 0.9.

sources at each hop of the periodic source's route, it can be shown that the upper bound of the jitter at the kth hop is on the order of N^kT. It is clear from the figure that evolution of the jitter distribution is characterized by an increase in the clumping as well as the dispersive effects. The tail of the distribution has been magnified to reveal the non-decaying nature of the jitter distribution. This is in contrast to the fast decaying tails observed in [1] in the presence of renewal interfering traffic. The long tails of the jitter distribution in the presence of bursty interfering streams suggest that the synchronization process can be severely affected unless jitter control is enforced at the switching points.

The problem of traffic distortion in periodic streams can be addressed by assigning cell-level priorities to such real-time sources. As pointed out earlier, non-periodic streams are also subject to severe distortion in the presence of highly bursty interfering traffic. Figure 8 compares the end-to-end delay distributions of a single ON-OFF source in the presence of geometric and bursty, non-renewal interfering traffic respectively. A multiple hop model comprising three switches in tandem with background traffic regenerated at each switch was simulated to obtain the delay distributions. Superposition of three ON-OFF sources was used to represent non-renewal interfering traffic. The ON-OFF sources have a mean burst

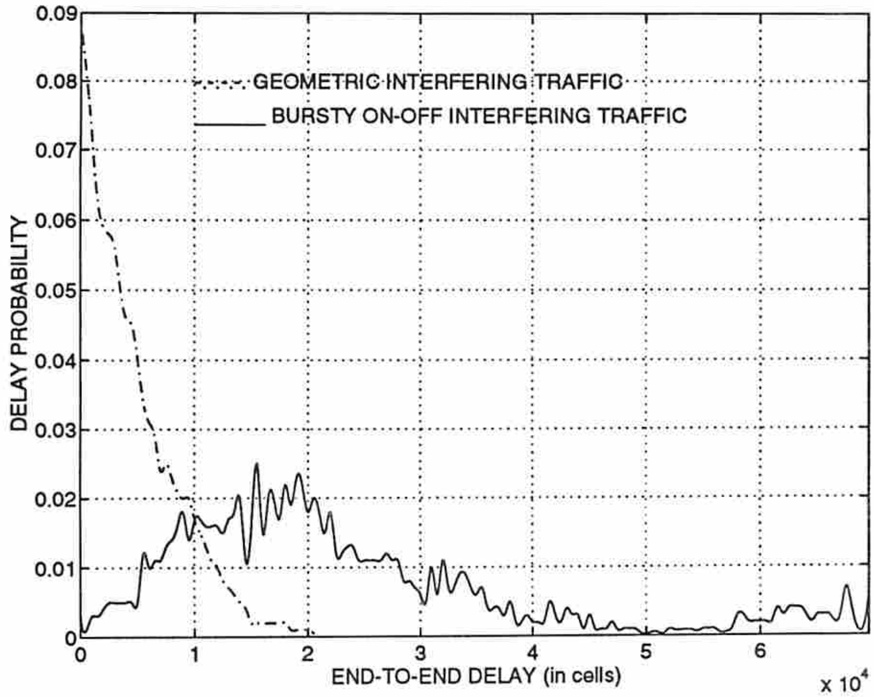

Figure 8: Comparison of end-to-end delay distributions of an ON-OFF source for the case of geometric and bursty interfering traffic respectively. A multi-hop model comprising three switches in tandem with background traffic regenerated at each switch is simulated for this plot. Each switch is driven at an utilization of 0.9.

duration of 1000 slots. While higher mean end-to-end delays are not surprising in the case of bursty interfering traffic, the long tails suggest that tight delay bounds are difficult to provide with a simple statistical transport mechanism.

6 Discussion

In this paper, we have investigated the distortion suffered by a periodic source in the presence of a superposition of ON-OFF traffic streams. Jitter has been associated with the variations of the queue size at the arrival instants of periodic customers. This definition is equivalent to the jitter defined as the variations in the waiting times of successive periodic customers. Later, we relax the requirement of periodicity and investigate the departure process of any arbitrary renewal arrival process. We feel that this study is closely related to the self-similar nature of broadband traffic reported in [6].

We show that cells belonging to the periodic source cluster together for high values of the mean burst duration of the interfering ON-OFF sources. The departure stream, as observed at the multiplexer's output port, bears little resemblance to the original periodic traffic stream. This severe distortion manifests in increased bandwidth requirements at the latter multiplexing stages of the connection. Admission control protocols should take into account this change in traffic characteristics of a connection, as it traverses the network. This traffic distortion is not limited to periodic sources alone. The departure distribution of any arbitrary renewal arrival process bears little resemblance to the original arrival distribution in the presence of highly bursty background traffic streams. This manifests in increased clumping as well as dispersive effects in the departure distribution. It is clear that while statistical multiplexing enables efficient and cost-effective transport, jitter control at the intermediate switching points is necessary for guaranteeing the QOS requirements of real-time traffic.

Traffic shaping approaches such as Stop-and-Go Queueing [3] and Virtual Clock [11] may be useful in reducing the degree of distortion. However, these approaches result in low network resource utilizations. Schemes that shape traffic effectively but do not compromise netork efficiency require further study.

In the future, we would like to characterize, quantitatively, the changes in bandwidth requirements of a connection at subsequent switches, that would be required to support its desired QOS. This involves approximating the departure process with familiar source models and computing its effective bandwidth. Another direction we are interested in pursuing, concerns the jitter as it evolves in a network of queues.

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