ATM Test Traffic Generation Algorithms

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Abstract

Although many theoretical studies have been carried out to evaluate the performance of asynchronous transfer mode (ATM) networks, measurement equipment and techniques are required to analyze real ATM traffic and to compare the data with theoretical models. This paper describes the theory and application of test traffic-generation methodologies that are being implemented with an ATM Traffic Analyzer. This Traffic Analyzer generates ATM test cells based on a user-selectable statistical distribution. At the receiving end, the Traffic Analyzer produces performance metrics to validate ATM switch and network performance. The Traffic Analyzer measures and computes performance parameters such as cell loss, cell delay, cell delay variation, and cell error. Here we describe mathematical algorithms that can be used to generate various constant-bit-rate and variable-bit-rate traffic patterns, and give examples for data, voice, and video sources.

I. Introduction

Asynchronous transfer mode (ATM) is a high-speed packet-switching technique employing short fixed-length packets, called cells [1]–[4]. The 53-byte cell has a 5-byte header containing the ATM layer protocol control information, and a 48-byte information payload. The principle of ATM is to format the traffic streams from widely differing types of services (voice, video, data, *etc.*) into cells, and then use asynchronous time-division multiplexing to transport these cells over a single channel in a network. This allows ATM to handle the diverse requirements of highly bursty, real-time, loss-tolerant traffic such as interactive voice and video, in addition to continuous, loss-sensitive data traffic, which needs high throughput and strict error control but can tolerate some degree of delay. Consequently, ATM presents a single, flexible, integrated switching mechanism that can support a wide spectrum of multimedia services such as variable-bit-rate (VBR) packetized voice, constant-bit-rate (CBR) traffic, compressed and full-motion video, imagery, and various classes of data.

When implementing ATM switches, one needs to verify their performance in networks under various traffic load conditions. Of particular importance to traffic engineering are the measurements of cell loss, cell delay, cell errors, and cell delay variation. Cell losses and cell transmission delays indicate the degree of network congestion, whereas cell errors indicate the fidelity of the transmission link. Variations in cell delay, or jitter, can arise from the process of multiplexing cells from different multimedia sources, which generally exhibit a diverse mixture of traffic characteristics with different correlations and burstiness parameters. Although these problems have been studied extensively both theoretically and through computer-based simulations (e.g., [5]–[10]), test instruments and associated test techniques are required to measure performance in real networks with actual traffic.

This paper addresses the implementation of an ATM Traffic Analyzer that generates user-selectable distributions of ATM test cells to enable performance measurements in terms of cell loss, cell delay, cell delay variation, and cell error under different traffic loads. Section II describes the basic operation of the ATM Traffic Analyzer. Section III discusses how to use this equipment to carry out quality of service (QOS) performance measurements, which standards bodies such as the ITU-T and user groups such as the ATM Forum are examining. The mathematical models for various distributions of the active and idle cell patterns are addressed in Section IV. In Section V, we describe how to select cell patterns to model ATM traffic with some fraction of the trunk bandwidth. The simulations of CBR and VBR traffic are discussed in Sections VI and VII, respectively.

Figure 1 is a top-level block diagram of the ATM Traffic Analyzer [11]-[12]. The four basic modules are a Test Cell Generator (TCG) which creates the test cell traffic stream, a Test Cell Receiver (TCR) which analyzes the received traffic, Network Interface cards for adapting to a particular type of ATM physical layer format, and a

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personal computer-based Control Module for the human-machine interface (HMI) to the Traffic Analyzer.

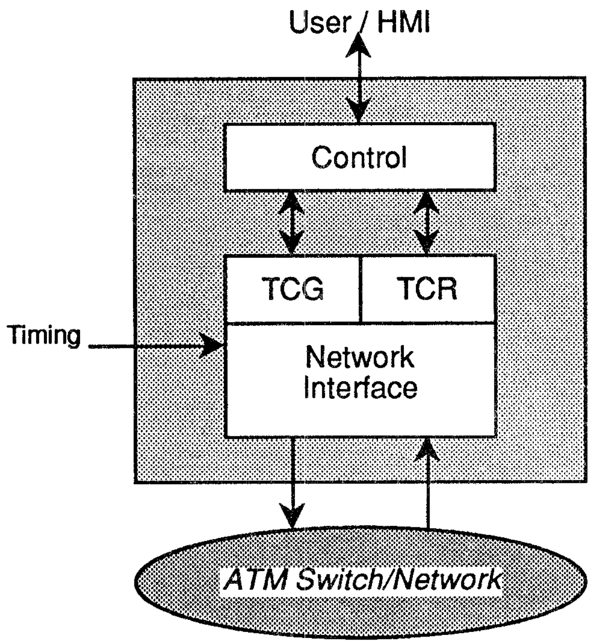

Fig. 1. The basic functional modules of the ATM Traffic Analyzer

II. ATM Traffic Analyzer

A. Test Cell Generator

The fundamental function of the Test Cell Generator is to create varying levels and distributions of ATM traffic streams, based on statistical distributions specified by the user. This is accomplished by using the contents of an active-cell distribution random access memory (active RAM) and an idle-cell distribution RAM to control the lengths of the active bursts and idle-cell gaps, respectively. The RAMs are loaded prior to running the TCG, so as to give the desired traffic distribution. If, for example, a fraction p of the bursts in a desired test traffic pattern is to be of length N (in units of cells), then that fraction of the active RAM locations is loaded with the value N.

Once the RAMs are loaded, the TCG creates a user-specified traffic pattern containing active ATM-formatted cells with valid headers, and sends it to a source ATM node. The cell destinations are also user-selectable, with full access to the VPI/VCI address space, and each field of the standard header is fully user-configurable. The TCG can specifically address ATM test cells to four independent test cell receivers, and can also address cells as background traffic to as many as 4095 other destinations. By using several TCGs, this background traffic can serve the need of stressing an entire small-scale local area network, or selected nodes of a wide area network.

Table I Format of the ATM test cell

Header	Cell Sequence Tag	Cell Time Tag	PN Sequence
Bytes 1–5	Bytes 6–8	Bytes 9–11	Bytes 12–53

Table I shows the ATM test cell format. The information field contains a three-byte cell sequence tag, a three-byte cell time tag, and a 42-byte PN sequence tag. The cell sequence tag is unique for each intended TCR on the network; it is used to determine cell loss. The cell time tag is relative to the single timing reference used by both the TCG and TCRs; it is used to determine cell transmit time. The PN sequence tag is a bit pattern created by a seed formed from the sequence and time tags; it is used for cell error analysis at the receiver.

B. Network Interface Module

The Network Interface module interfaces with both the TCG and TCR. As such, it is responsible for the ATM layer functions, as well as maintaining and adapting to the particular type of physical layer interface required to transmit to and receive cells from the ATM network.

To facilitate clock recovery, the transmit side of the Network Interface scrambles the payloads of all ATM cells received from the TCG. Likewise, on the receive side the Network Interface descrambles all payloads of ATM cells received from the external network interface and destined for the TCR. The self-synchronizing scrambler polynomial has the form $x^{43}+1$, in accordance with ITU-T Recommendation I.432 [13].

Cell delineation is performed on the incoming ATM cell stream to identify the start and end of cells. The cell delineation algorithm is in accordance with ITU-T Recommendation I.432. If cell delineation detects a header error by means of the Header Error Check (HEC), the cell is considered invalid and thus will be interpreted as a lost cell at the receiver. Cell header error correction does not occur, to avoid masking problems in the network being tested. The Network Interface does provide indications of header validity for each cell transmitted to the TCR.

When a test cell exits from the ATM switch or network segment being tested, it enters the cell-synchronization section on the receiver side of the

Network Interface Module. After it synchronizes on the 53-byte ATM cells of the incoming bit stream, this section calculates the header error check (HEC) on each cell. The Network Interface Module then forwards the test cell traffic stream, the synchronization signal, and the HEC signal to the TCR.

C. Test Cell Receiver

The TCR uses a digital signal processor (DSP) to examine the payloads of the valid test cells. Using the information in the cell-sequence, cell-time, and the PN-sequence tags (see Table I), the DSP computes the following performance variables:

N_t	number of cells transmitted
N_r	number of cells received error free
N_L	number of cells lost
N_{mi}	number of misrouted cells
N_e	number of errored cells
T_m	measurement interval

Upon completion of the measurements and analyses, the TCR forwards these values to the Control Module for real-time and time-averaged user display and further statistical analysis. The TCR groups the cell delay values, given as multiples of the cell period, into ten user-configurable ranges. The six primary network performance parameters, defined in ITU-T Recommendation I.35B [14], which the Test Cell Analyzer calculates from the measured variables are cell transfer delay, cell delay variation, cell loss ratio, cell error ratio, cell misinsertion rate, and cell transfer capacity.

III. Cell Generation Distributions

As described in Section II, the TCG uses RAM tables to drive the generation of cells for use in testing the switching system. The software explicitly supports four different distributions for numbers of contiguous active cells and numbers of contiguous idle cells. It is based on a given probability density function $f(x)$, which gives the probability that the number of contiguous cells (active or idle) is x. In what follows, $f(x)$ is a discrete distribution, and x can take on only integer values.

The active and the idle RAMs both have 2^{14} addresses. Let the contents of address k be R_k. The 16-bit width of the RAM storage limits these values to

$$0 \le R_k < 2^{16}, \quad \text{where } 0 \le k < 2^{14} \quad (1)$$

Each RAM table entry is selected with equal probability. Consequently, we get the desired distributions if a fraction $f(x)$ of the RAM entries have the value x. We see how this is done explicitly for four different distributions.

A. Constant Distribution

The constant distribution,

$$f(x) = \begin{cases} 1 & x = C \\ 0 & otherwise \end{cases} \quad (2)$$

gives an entirely trivial mapping,

$$R_i = C \quad (3)$$

Naturally, the parameter C must be an integer in the range $0 \le C < 2^{16}$.

B. Uniform Distribution

The uniform distribution is given by

$$f(x) = \begin{cases} \dfrac{1}{b-(a-1)} & a \le x \le b \\ 0 & otherwise \end{cases} \quad (4)$$

where the parameters a and b are integers that satisfy $0 \le a \le b < 2^{16}$.

C. Exponential Distribution

The exponential distribution is given by

$$f(x) = \lambda \, e^{-\lambda x} \quad (5)$$

It has a mean value equal to $1/\lambda$. Because RAM entries have a finite width, the distribution is truncated.

D. Gaussian Distribution

The Gaussian (or normal) distribution is given by

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2 / 2\sigma^2} \quad (6)$$

As with the exponential distribution, this is a probability density function, rather than a discrete distribution. It too is truncated because of the finite RAM width.

IV. Traffic Patterns

For purposes of measuring performance, it is necessary to model ATM traffic with a bandwidth that is some fraction of the trunk bandwidth. This is achieved by having some fraction of the cells be active, and the others be idle. The particular pattern of active and idle cells characterizes the nature of the traffic. Three useful traffic characteristics are its peak cell rate, sustainable cell rate, and burstiness.

Peak Cell Rate

ATM Forum and ITU-T standards documents, [15]–[16], define the peak cell rate of ATM traffic by means of a monitoring algorithm, called the generic cell rate algorithm (GCRA) in [15], which identifies individual cells that are too closely spaced. More precisely, they give two different algorithms, called the "virtual scheduling algorithm" and the "continuous-state leaky bucket algorithm," which are easily seen to be equivalent. Both are presented in [15] as flow charts; for simplicity of presentation, we rewrite the former in a higher-order language.

Suppose that we wish to test whether a given stream of cells has a peak cell rate of R, and hence a peak emission interval of $T = 1/R$. We select a cell delay variation tolerance of τ. Let the arrival times of the cells be t_k. The monitoring is performed by the following algorithm:

$\hat{t} \Leftarrow t_1$
for $k = 1$ **to** ∞ **do**
  if $t_k < \hat{t} - \tau$ **then** declare t_k noncompliant
  $\hat{t} \Leftarrow \max(\hat{t}, t_k) + T$

If there are no arrival times that are noncompliant, the traffic does not exceed a peak cell rate of R, with a cell delay variation tolerance of τ. Following [15], we will use the terminology that "the cell stream conforms to $\text{GCRA}(T, \tau)$" to indicate that no arrival times are declared noncompliant with the given parameters.

Sustainable Cell Rate

The sustainable cell rate R_s of traffic is its long-term average rate. If this is less than the peak cell rate, then we require a specification of how to measure this rate; that is, we need an operational definition of what is meant by long-term average.

To characterize burstiness, we consider a sequence of alternating bursts, at a peak cell rate R, and idle periods. Let the length of burst number n be Δ_n, and let the length of the succeeding idle period be I_n. Then, let $\bar{\Delta}$ be the average burst length and $\bar{I}$ be the average idle period. We define the average rate of the traffic to be

$$\bar{R} \equiv \frac{\bar{\Delta}}{\bar{\Delta} + \bar{I}} R \tag{7}$$

It is easy to see that $\bar{R}$ is just the long-term average rate at which active cells are transmitted; *i.e.*, it is equal to R_s.

Burstiness

Traffic with a peak cell rate R and an average cell rate $\bar{R}$ is characterized by the average-to-peak ratio,

$$\alpha \equiv \frac{R_s}{R} = \frac{\bar{\Delta}}{\bar{\Delta} + \bar{I}} \tag{8}$$

or, alternatively, by its burstiness, which is defined to be

$$\beta \equiv \frac{1}{\alpha} = \frac{R}{R_s} = \frac{\bar{\Delta} + \bar{I}}{\bar{\Delta}} \tag{9}$$

V. Constant Bit Rate Traffic

Constant Bit Rate (CBR) traffic is characterized by a constant or persistent data rate over a prolonged period, such as digital video and/or 64-kb/s digital voice. In this section we first characterize CBR traffic and then show how to simulate it with the Test Cell Analyzer.

A. CBR Traffic Characterization

Suppose that we have an idealized traffic source that provides data at a rate of one ATM cell every $T = 1/R$ seconds. Suppose further that the source issues request to send (RTS) flags at exactly R to a channel of capacity $R_{\text{cell}} = 1/T_{\text{cell}}$. By definition, the resulting sequence of cells is constant bit rate traffic, using a fraction R/R_{cell} of the available bandwidth. To understand the CBR traffic characteristics more clearly, we first look at two specific traffic loadings, and then describe the general case.

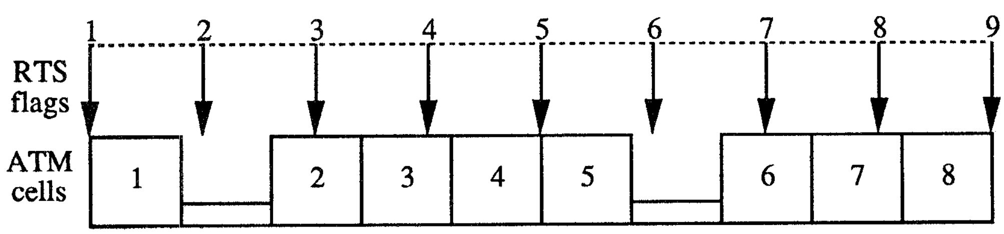

Figure 2 CBR Traffic with 80% Loading

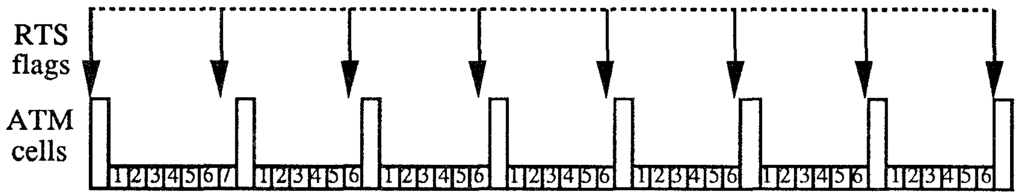

Figure 3 CBR Traffic with 14% Loading

As one example, consider 80% loading, so that $R = \frac{4}{5} R_{cell}$. Figure 2 shows the resulting pattern of active and idle cells. We assume that the first RTS flag is issued just before a cell epoch, so that the source data is sent as that cell. The second RTS flag will miss the next cell epoch, so the next cell will be idle; the data is sent as the third cell. The pattern repeats after four RTS flags and five cells.

Not all CBR traffic has such a simple pattern. The second example, 14% loading, gives a more complex pattern, shown in Figure 3. There is a subpattern of one active cell, followed by six idle cells. This subpattern is repeated seven times, after which there is an additional idle cell. Thus, the overall pattern contains 50 cells, of which 7 are active and 43 are idle. In particular, the active cells are not uniformly distributed, although the deviation from uniformity is small.

We now consider how to use the TCG to simulate CBR traffic for which the loading has a rational value, equal to n/d when expressed in lowest terms. If either n or $n-d$ is unity, we load all entries of the active RAM with n and all entries of the idle RAM with $n-d$. Otherwise, the simulation is more complicated.

We first consider loadings less than or equal to $\frac{1}{2}$. We use integer division with remainder to write

$$d = k\,n + r, \qquad 0 \le r < n \tag{10}$$

The quotient k is at least 2 because so is d/n. We rewrite (10) as

$$d = (n-r)k + r(k+1) \tag{11}$$

This describes an overall pattern of length d, made up of $n-r$ subpatterns of length k and r of length $k+1$. Each subpattern has a single active cell and the rest idle cells. Consequently, we set all active RAM entries to 1. We set a fraction $(n-r)/n$ of the idle RAM entries to $k-1$, and the remaining r/n entries to k. If r is 0, as it is if and only if n is 1, then there are no subpatterns, and all idle RAM entries are set to $k-1$.

For loadings greater than $\frac{1}{2}$, we reverse the roles of active and idle cells. That is, we construct RAM entries for CBR traffic with loading $(d-n)/d$ and then swap the contents of the active and idle RAMs.

B. CBR Traffic Simulation

In this section, we give typical parameters for simulating CBR traffic types with the TCG. Specifically, we will look at digitized voice and constant-rate video. For the sake of definiteness, the following calculations are done with a 44.736 Mb/s data rate (DS-3). Furthermore, the only cell overhead for which we allow is the 5 header bytes per cell. That is, we do not include the physical layer convergence protocol (PLCP) overhead.

(1) Digitized Voice. Suppose that we wish to model digitized voice without silence detection, with a data rate of 64 kb/s. Allowing for overhead, this requires 0.158% of the available bandwidth; this is very close to $\frac{1}{633}$. We model this by setting every active RAM entry to 1, and every idle RAM entry to 632. This produces CBR traffic with a data rate of 64.006 kb/s.

(2) Constant-Rate Video. Suppose that we wish to model a constant-rate video channel, with 2 Mb/s. Allowing for overhead, this requires 4.936% of the available bandwidth. We model this as CBR traffic with $\frac{4}{81}$ loading. Integer division with remainder gives $81 = 20 \times 4 + 1$. Consequently, as discussed above, we set every active RAM entry to 1; we set $\frac{3}{4}$ of the idle RAM entries to 19, and the remaining $\frac{1}{4}$ to 20.

VI. Variable Bit Rate Traffic

Variable bit rate (VBR) traffic is defined by a peak cell rate R and an average cell rate $\bar{R} < R$. We have the corresponding emission intervals $T = 1/R$ and $\bar{T} = 1/\bar{R}$. Examples of VBR traffic are bursty data traffic, image files, large database file transfer, packet video, and packet voice. In this section we first characterize VBR traffic and then show how to simulate it with the Test Cell Analyzer.

A. VBR Traffic Characterization

Suppose that every entry in the active RAM is set to the value M, and every entry in the idle RAM is set to the value $N-M$. The M contiguous active cells constitute a burst at a peak rate of R_{cell}. The average rate is

$$\bar{R} = \frac{M}{N} R_{cell} \tag{12}$$

The TCG is also capable of simulating traffic with a peak rate less than R_{cell}. Suppose the peak loading is n/d and the average loading is ρ. We will simulate this by means of a two-state Markov process. One state, which occurs with proabililty λ, has CBR traffic with loading n/d. The other state has L consecutive idle cells. We simulate this in the TCG by setting a fraction $\lambda(n-r)/n$ of the idle RAM entries to $k-1$, a fraction $\lambda(r/n)$ of the entries to k, and the remaining $1-\lambda$ of the entries to L. (For simplicity, we assume that n/d is less than $\frac{1}{2}$.) We set every active RAM entry to 1.

The average number of times the CBR Markov state occurs sequentially is $1/(1-\lambda)$, and so the average burst length is

$$\begin{aligned} \bar{\Delta} &= \frac{1}{1-\lambda}\left\{\frac{n-r}{n}k + \frac{r}{n}(k+1)\right\} \\ &= \frac{1}{1-\lambda}\frac{d}{n} \end{aligned} \tag{13}$$

Similarly, the average idle period is

$$\bar{I} = \frac{1}{\lambda} L \tag{14}$$

These equations specify the simulation parameters λ and L in terms of macroscopic properties of the traffic. We use (8) to write

$$\rho = \frac{\bar{\Delta}}{\bar{\Delta} + \bar{I}} \frac{n}{d} \tag{15}$$

from which we find the average loading ρ.

We note that this simulation has active cells in some idle periods, spaced by L. For large values of L, which we see below are typical of many useful simulations, this is a negligible perturbation. Moreover, the probability λ is typically near unity, and so sequential occurrences of the idle Markov state are relatively improbable.

In this approach to VBR simulation, the additional idle cells have a constant distribution. They can be given any desired distribution; the calculation of the simulation parameters is similar, though more involved.

B. VBR Traffic Simulation

In this section, we give typical parameters for simulating VBR traffic types. As with CBR, we use a 44.736 Mb/s data rate (DS-3), and allow only the 5 header bytes per cell overhead. The specific traffic types we consider here are digitized voice [17]-[18], bursty video [19], relatively smooth data traffic and bursty interactive traffic [20].

(1) Digitized Voice. As with CBR traffic, we can get a 64-kb/s peak rate by a loading of $\frac{1}{633}$. If the average voice burst is 0.35 s, we have $\bar{\Delta} = 36928$. We then use (13) to find λ; it is 0.9829. We would like the idle periods to average 0.65 s. When we use this in (15), however, L slightly exceeds the maximum possible with the TCG. Instead, if we let L be $2^{16}-1$, we get an average idle period of 0.632 s. The impulsiveness is 2.81.

With this choice of modeling parameters, we simulate digital voice by loading all active RAM entries with 1. In the idle RAM, 16103 entries are loaded with the value 632; the remaining 281 entries are loaded with 65535.

(2) Bursty Video. Bursty video can be modeled with a peak loading of $\frac{4}{81}$, giving a peak rate of 2 Mb/s. We pick an average burst length of 0.025 s, and an average idle period of 0.620 s. (These are scaled down by a factor of 20 to preserve the burstiness, 25.8, while not exceeding the RAM width.) We find λ to be 0.9923 and L to be 64914. We simulate bursty video by loading all active RAM entries with 1. In the idle RAM, 12194 entries are loaded with the value 19; 4065 entries are loaded with 20; the remaining 126 entries are loaded with 64914. Figure 4 shows typical simulated traffic with these parameters.

(3) Relatively Smooth Data Traffic. For this type of traffic, the ratio of average-to-peak bandwidth is relatively high and the bursts at peak speed are fairly short and nearly constant. Since this traffic has nearly constant burst and idle periods, we chose to model them as Gaussian with small standard deviations. Almost any distribution with a small standard deviation would suffice; we select a Gaussian distribution for simplicity. We have one selectable parameter, the mean value

$$\mu_\Delta \equiv \bar{\Delta} \tag{16}$$

of the burst lengths, in cells. As noted above, these bursts consist of contiguous active cells, and so the peak rate is R_{cell}. The mean value of the idle periods is given by

$$\mu_I \equiv \bar{I} = \frac{1-\alpha}{\alpha} \mu_\Delta \tag{17}$$

where the average-to-peak bandwidth ratio α should be moderately large, say $0.1 < \alpha < 1$. The standard deviations of the two distributions are

$$\sigma_\Delta = \varepsilon\, \mu_\Delta \tag{18}$$

$$\sigma_I = \varepsilon\, \mu_I \tag{19}$$

where the parameter ε should be small, say 0.01, in order to ensure nearly constant periods.

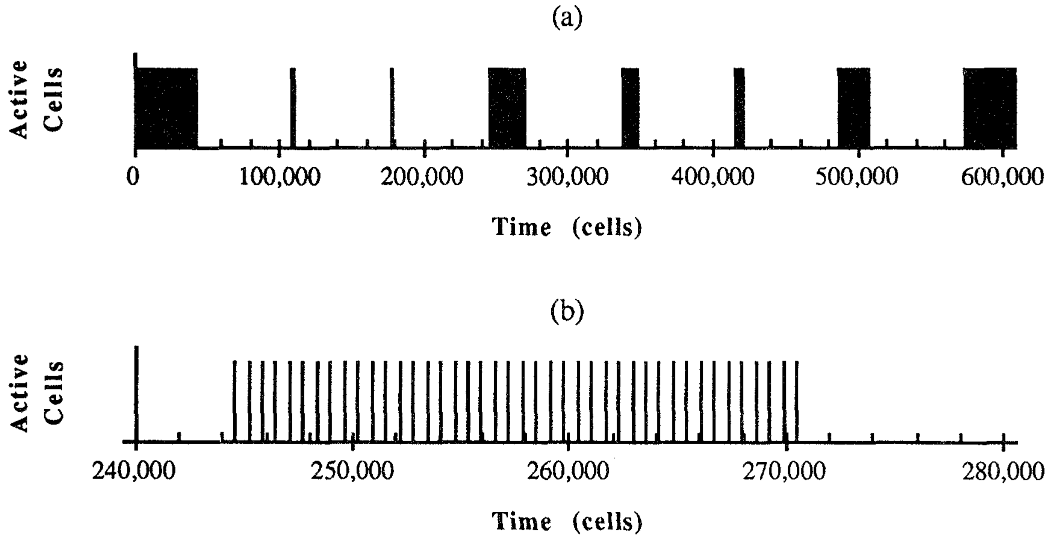

Figure 4 Simulated Bursty Video Traffic
(a) Overall (b) Detail of One Burst

Suppose that we want to simulate a mean burst length of 1000 cells, which is equivalent to 9.5 ms, and an average-to-peak ratio of $\alpha = 0.2$. For the active RAM distribution, we need a mean of $\mu_\Delta = 1000$ and a standard deviation of $\sigma_\Delta = 10$. For the idle RAM distribution, we need a mean of $\mu_I = 4000$ and a standard deviation of $\sigma_I = 40$.

(4) Bursty Interactive Traffic. This type of traffic is characterized by moderately short bursts of data and idle periods. We can think of the start and stop times as random events that are reasonably modeled as Poisson processes. If arrival times are Poisson distributed, the inter-arrival times are exponentially distributed. This suggests an exponential distribution for the burst and idle period lengths.

The use of an exponential distribution means that the mean values completely specify the data bursts. These means are given by (16) and (17). The average-to-peak bandwidth ratio α should be moderately small, say $0.001 < \alpha < 0.1$.

Suppose that we want to simulate a mean burst length of 100 cells and an average-to-peak ratio of $\alpha = 0.002$. Then the active RAM distribution is given by $\mu_\Delta = 100$, and the idle RAM distribution is given by $\mu_I = 50000$. Because the mean idle time is near the upper limit 2^{16} of the RAM capacity, the idle distribution will be clipped to a degree, and so will have somewhat fewer long idle periods.

VII. Summary

To evaluate the performance of broadband networks employing ATM switches, traffic engineers require measurement equipment and techniques to analyze the effects of various types of ATM traffic. To assist in this task, this paper has described the operation and implementation of an ATM traffic analyzer. This instrument generates a variety of user-selectable stochastic traffic patterns for testing ATM switching networks. Using these traffic patterns, the equipment evaluates quality-of-service parameters such as cell loss, cell delay, cell delay variation, and cell error rate.

The Test Cell Generator we described uses RAM tables to drive the generation of cells for testing ATM switching systems. The tables are loaded with user-selectable traffic patterns. The ones we illustrate here are constant, exponential, Poisson, and Gaussian distributions. Using these distributions, we show how to model and simulate various types of constant-bit-rate and variable-bit-rate test traffic. In particular, we show how to load the Traffic Analyzer to simulate digitized voice, constant-rate video, bursty video, and bursty data traffic streams.

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