ATM Traffic Characterization

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Abstract

This paper treats characterization of ATM traffic. As the connection acceptance control, the policing and last but not least the terminal equipment are concerned with traffic characterization, this issue is of special importance. This paper first develops theoretical traffic characterizers to be used in theory and simulation, and proposes then a single parameter - the Equivalent Offered Traffic - to be implemented to characterize ATM traffic. This parameter has the advantage of being simple, policeable and allows to use linear CAC algorithms.

1 Introduction

This paper considers Integrated Broadband Communication Networks (IBCN) based on the Asynchronous Transfer Mode (ATM). In ATM, data is packed into cells of equal length which are sent individually over the network. At the destination site, the cells are unpacked into the original bitstream. The time axis is divided into slots. During one slot exactly one cell can be transmitted. The transfer mode is called asynchronous because there is a priori no periodicity in the cell stream belonging to a certain connection (no frames like in STM). Generally, cells are transmitted in any vacant slot. The cell stream depends therefore directly upon the original bitstream, i.e. if the latter is variable in the time, so will be the former. This variability may be caused by data compression techniques that produce more or less bits according to the redundancy of the data to be transmitted (e.g. a video codec). The conception of an ATM switch has therefore to take into account these statistical variations. The switching mode for ATM widely agreed upon is based on the Statistical Multiplexing (SM).

Statistical multiplexing means that cells are in principle switched at the very moment when they arrive at the switch. In practice, however, it may happen that there is no vacant slot available at the appropriate outlet so that the cell has to wait until there is one. The switch must therefore be equipped with memory to store temporarily the waiting cells. There are many different switching architectures: the memory may be implemented in form of input buffers or output buffers, individually for each inlet, resp. outlet, or there may be one single memory that is shared by all inlets and outlets jointly. The architecture considered in this paper has individual output buffers for each outlet (Fig.1).

Fig.1: Structure of a simple ATM switch

The fact that the output buffers are limited in capacity means that, in times of extraordinary heavy traffic, there may be no space left in the buffer for an arrived cell. In this case the cell is lost. Naturally, cell losses have to be limited to a strict minimum. There are two network entities that watch that the Cell Loss Rate (CLR) does not exceed a certain nominal value (e.g. 1:10^9): the Connection Acceptance Control (CAC) and the Source Policing (SP). In fact they do not only watch over the CLR, but also over other Quality Of Transfer (QOT) parameters like cell delay and cell delay jitter. In this paper, however, only the CLR is considered.

The connection acceptance control is an algorithm that decides whether or not a connection with a certain statistical behaviour can be accepted on a determined link without increasing the CLR over the nominal value. This decision has to be taken for each link along a route through a network, because the load on the links is different and also because the statistical variations of the requesting connection are modified by the multiplexing process. The CAC is therefore a local procedure and is invoked by the global Call Control (CC). The call control is the algorithm whose tasks beside others are to negotiate with the terminal equipment (TE), to find a route through a network and to establish an accepted connection. In the negotiations (normally they will be...
done automatically between CC and the TE the parameter of the statistical variations are layed down in a so-called contract. The contract parameters are then passed on to the CAC which takes its decision according to the new contract and the contracts of the already established connections. If the CAC is ok for all links of a route, then the contract is ratified and the connection will be established.

Once the call is in progress, the network has to watch that the TE does not send more cells than it is allowed to according to the contract. This is the task of the source policing (SP). It is situated just after the ATM source. Many ways have been proposed to do SP and one of the best known is the so-called Leaky Bucket (LB). The leaky bucket consists in principle only of a counter that is incremented with each arriving cell and decremented at a constant rate, the leak rate. The contents of the counter are considered as credits with respect to cell transmission, i.e. cells can pass as long as the number of credits is smaller than a certain value. When the number of credits is going to exceed this limit, the SP takes certain measures. The most simple one is to discard the cell causing the excess. But there are other possible measures like violation tagging (the cell is discarded preferably in case of buffer overflow) or the cell is buffered until the credits become again smaller than the limit.

2 Conditions for Contract Parameters

As evoked in the introduction, the characterization of ATM traffic is one of the central problems of network conception. At least three entities of the system, the TE, the SP and the CAC, supply or need information about the statistical properties of a source. In order to prevent inaccurate parameter translations between these different entities, it is desirable that all of them work with the same characterization parameters. This implies the need for a good choice of the parameters, because the conditions of all three units have to be fulfilled together. These conditions are:

Simplicity
To facilitate the communication between the TE and the call control, the parameters must have a meaning as simple as possible. Besides, the TE normally even does not know much about the statistics of its traffic so that it can only give the values of the most simple parameters.

Accuracy
Bad estimations of QOT parameters by the CAC may cause wrong decisions. A requested traffic may be accepted although it is going to deteriorate too much the QOT, or a requested traffic is refused, although the resulting QOT would still lie within the nominal bounds. Therefore, parameters have to be found that lead to good QOT parameter estimations. Having said that, it must be clear that the CAC must work very fastly provided that there may be dozens of call attempts per second.

Policeability
The function of the source policing is to protect the system against malicious users or malfunctioning equipment. It must therefore know how to check the contract parameters. Statistical contract parameters like the mean cell rate cannot be policed exactly, because the SP can only estimate their values and these estimations may exceed the contract values for a short period of time. In this case the SP would take measures without really having to. In order that the SP can effectively protect the network (and the subscriber against "hysteric" measures), it is indispensable that the traffic characterization parameters must be policeable.

The next sections investigate a set of traffic characterization parameters that will be checked against the forestated conditions.

3 Influence of the Arrival Pattern on the Buffer Occupancy

The statistical variations of the contributary cell streams have to be known by the network in order to estimate the QOT parameters. For Constant BitRate (CBR) traffic, there are no statistical variations and thus there is no further problem. For Variable BitRate (VBR) traffic, however, one may suppose them to be stochastic processes with certain regularity properties. In this case, the statistical variations may be given by the mathematical description of the stochastic process. Nevertheless, such a full description is far to complicated to be layed down in a contract between the TE and the network. Therefore one has to find a small set of simple parameters that are strong enough to allow a good estimation of the QOT parameters.

As in this paper the only QOT parameter considered is the CLR, one has to derive the traffic characterization parameters from an investigation of what statistical properties of a cell stream have an influence on the buffer occupancy. To this end consider a multiplex with m1 inlets, where inlet number 1 carries the cell stream under consideration (CSUC) and the remaining m1-1 inlets constitute the background traffic (BT). The BT is very important, because it has a great influence on the traffic characteristics of the system and particularly those of the cell stream under consideration. Without background traffic there is no delay in the multiplexer and the cells of the CSUC pass transparently. To investigate the multiplexer system one has therefore to define one or preferably several BTs in order to study the influence of the CSUC on the buffer. It is advantageous to use one BT process with batch arrivals instead of a lot of individual BT processes.

Fig.2 shows two different CSUC with the same mean Cell Arrival Rate (CAR) offered to a multiplexer. Each hatched rectangle depicts a full cell and each white one an empty cell. The BT has been chosen so that it is
equivalent to a reduction of service rate available to the
CSUC to 50% of its maximum value. This is a very
special agreement; however, the phenomenon to be
investigated in the following remains essentially the same
for other BT as long as the available service rate is higher
than the CSUC's arrival rate.

It is easy to see that the more slowly the CSUC arrival
pattern varies, the more the buffer occupancy is high. It is
clear that for a high buffer maximum also the CLR is
high. So, if it is possible to measure this "velocity of
variations" for more general - especially stochastic -
traffics, one has a parameter that influences strongly the
cell loss rate. However, before trying to define such a
velocity, an important random variable is introduced.

4 The Instantaneous Cell Arrival Rate

This random variable is the *Instantaneous Cell Arrival
Rate* (iCAR), denoted by the random variable $X_n$. If one
defines the random variable $Y_i$ to denote the content of
cell number $i$, i.e. $Y_i=1$ if the $i$-th cell is full and $Y_i=0$ if
the $i$-th cell is empty, then the iCAR is defined as the
number of cells arriving during an integration interval of
length $N$ divided by $N$:

$$X_n = \frac{Y_{n+1} + Y_{n+2} + \ldots + Y_{(n+1)N}}{N}$$

For reasons of simplicity, the stochastic process $Y_i$ is
considered to be wide-sense stationary\(^1\), which entails the
wide-sense stationarity of the process $X_n$. The most
important statistical values of the iCAR are the following:\(^2\):

- mean cell arrival rate $\lambda = EX$
- variance of cell arrival rate $\sigma^2 = VarX$
- peak cell arrival rate $m_0 = PeakX := \min\{ m / \text{Prob}[X \leq m] = 1 \}$
- coefficient of variation $cv = \frac{\sigma}{\lambda}$
- burstiness $\beta = 1 + \frac{\sigma^2}{\lambda^2} = 1 + \frac{VarX}{(EX)^2}$

The peak cell arrival rate ($pCAR$) is a special case of
the $\alpha$-quantile. The $\alpha$-quantile of a distribution $F$ is
defined to be that value $m$ such that the probability that a
random variate of $F$ is greater than $m$ is equal to $\alpha$, i.e.

$$\text{Prob}[X > m] = \alpha$$

This leads to the following definition of the $\alpha$-quantile:

$$\alpha\text{-quantile } m_\alpha = Q_\alpha X := \min\{ m / \text{Prob}[X \leq m] = 1 - \alpha \}$$

For $\alpha=0$ the $\alpha$-quantile is equal to the peak cell arrival
rate (this explains the index 0 of its symbol $m$).

In the case of stochastic processes with no hardware-
imposed maximum CAR, the $pCAR$ $m_0$ is not an
appropriate measure, because it would be frequently equal
to the link cell rate. A Bernoulli process, for instance,
may generate a sequence of full slots of any length
(although with a very small probability). It may be better
to use the $\alpha$-quantile (for $\alpha=0.5$ it equals the median) with
an $\alpha$ in the order of magnitude of $10^{-9}$ or similar.

The strong influence of the length $N$ of the integration
interval is hidden in these definitions. Only the mean cell
rate ($mCAR$) is independent of $N$, i.e. the value of $\lambda$ is
constant. But the pCAR for instance is equal to 1 for $N=1$
and tends to $\frac{1}{\text{shortest interarrival time}}$ for $N \to \infty$.

Because of the importance of this phenomenon, another,
more revealing, example is given: the behaviour of the
variance. Some algebraic work reveals that, $Y$ being a
wide sense stationary stochastic process, then

$$N \sigma_n^2 = C_Y(0) + \sum_{s=1}^{N-1} (1 - \frac{s}{N}) C_Y(s)$$

Taking the limit for $N \to \infty$ yields:

$$\lim_{N \to \infty} \frac{\sigma_n^2}{\Phi(0)} = \frac{1}{\lambda (1-\lambda)}$$

\(^1\)A stochastic process $Y_k$ is called wide sense stationary, if
$EY_k$ as well as $EY_k Y_{k+s}$ are independent of $k$. In this case the
covariance is defined as $C_Y(t) = EY_1 Y_{1+s} - (EY_1)^2$.

\(^2\)They may be indexed to indicate explicitly the length of the
integration interval, e.g. for $N=1$ one has $\sigma_1^2 = \lambda (1-\lambda)$. 
where

\[ \Phi(0) = \sum_{s} C_Y(s) \]

Now we are at the point where we can resume the reasoning about a definition of a "velocity of variations" for stochastic processes. Such a definition could rely on the following observation: for the periodic sources shown in Fig.2, the VOV could be defined as the reciprocal of the period length. The period length, on the other hand, is the smallest \( N \) for which the variance of the iCAR vanishes. For stochastic sources the variance normally does not vanish completely but will tend to zero according to (1), i.e. the faster the smaller \( \Phi(0) \). If one defines the period \( P \) as that \( N \) where the variance becomes eventually smaller than an \( \epsilon \)-limit, then \( P \) is approximatively proportional to \( \Phi(0) \) (Fig.3). The VOV could then be equated to the reciprocal of \( \Phi(0) \). It is, however, easier to use \( \Phi(0) \) directly. Hence the following definition: The sum of all covariances \( C_Y(s) \) is called Timescale parameter of a source and is denoted by \( \Phi(0) \).

It is advantageous to use a normalized version of the parameter \( \Phi(0) \). This normalization relies on the following representation of \( \Phi(0) \):

\[ \Phi(0) = \sigma_Y^2 \sum_{s} r_Y(s) \]

where the \( r_Y \) is the autocorrelation function (=autocovariance/\( \sigma^2 \)) of the \( Y \) process. By denoting the sum in the above formula by \( G \), one gets the definition of the Granularity of a source:

\[ \text{Granularity} := G = \sigma_Y^2 \Phi(0) \]

The advantage of \( G \) over \( \Phi(0) \) is that it is to a great extent free from the parameter \( \sigma_1 \) (and consequently from \( \lambda \)) and allows in this way to compare the granularity of CSUC with different offered traffic.

The value of \( G \) may be used to coarsely classify all CSUC into three types:

- \( 0 \leq G < 1 \): Thin traffic, characterized by the absence of contiguous blocks of cells. CBR belongs to this class.
- \( G = 1 \): Uncorrelated Bernoulli arrivals; traffic with Poisson distributed lengths of burst and silence periods.
- \( 1 < G \): More or less bursty traffic with "coagulating" cells.

To give an intuitive feeling for the \( G \) parameter, the
following three "barcodes" show examples of cell arrival patterns for \( \lambda=0.15385 \) and \( G=0.14686 \) (upper), \( G=1 \) (middle) and \( G=+1.85314 \) (lower):

A few papers show analytically the great influence of the granularity on the buffer usage. [BRU88] introduces a parameter \( K \) which is equal to \((G+1)/2\), and from which he concludes that it is an important parameter by giving an example. [LJ90] uses the parameter \( S_k=G-1 \) and underlines also the important role of \( S_k \) in queueing theory.

5 The Spectrum

Theoretical studies and simulations made by the author showed that the mCAR \( \lambda \) and the granularity \( G \) allow to estimate the mean queue length to an accuracy of one order of magnitude for arbitrary traffic. The estimation used was based on the 2-state Markov model (see below) which allows analytical results for buffer performance measures. Nevertheless, one would like to have a third parameter to increase the accuracy of the estimation by using a three parameter model. It seems to be natural that a third parameter has to describe the traffic variations in more detail than the granularity alone does. This section proposes the spectrum of a stochastic process as a basis for the research of this third parameter. The hope is that one will be able to extract such a parameter from the spectrum, i.e. the spectrum per se is not the result of the research, it is the way to the result.

Supposing again that \((Y_n)_{n \in \mathbb{N}}\) be a wide-sense stationary stochastic process, one can define the autocovariance function \( C(s) = \text{E}[Y_1Y_{1+s} - (\text{E}[Y_1])^2] \) which does not depend on \( n \). \( C(0) \) corresponds to the usual variance \( \sigma^2 = \text{VAR}(Y) \). The function \( C(s)/C(0) \) is called autocorrelation function, taking pattern from linear regression theory. Due to the Wiener-Khintchine theorem, the spectrum \( \Phi \) is obtained by Fourier transforming the autocovariance function. As the Fourier transform is an one-to-one transformation, the spectrum has the same validity as the autocovariance function, i.e. it describes the traffic variations. The spectra considered in this paper are all periodic and symmetric around the ordinate. The symmetry is due to the fact that the original data is real. The discrete definition domain of the covariance function is the reason for the periodicity of the spectrum.

The spectrum can be interpreted as the intensity of all velocities of variations: for any \( x \)-position, i.e. for any VOV, the \( y \)-position gives the relative strength of this particular VOV with respect to the others. Recalling the definition of VOV for periodic sources, it is clear that the maximal VOV is \( 1/2 \). The spectrum is therefore uniquely determined by the values in the interval \([0,1/2]\). The interpretation of the relative strength of a particular VOV poses some difficulties: based on the fact that the integral of a spectrum over the definition domain is equal to the variance \( \rho(1-p) \) \((\text{cell}^2)\), it is clear that the dimension of the ordinate must be \( \text{cell}^2/\text{slot} \). However, that does not help very much to interpret the meaning of "relative strength". Only for the value at position \( 0 \) \((\text{slot}^{-1}) \) it is possible to give an interpretation: it is not by incidence that the symbol \( \Phi \) for the spectrum is the same as the one used for the timescale parameter \( \Phi(0) \). By the definition of the spectrum, \( \Phi(0) \) is actually the sum of the covariances over all lags. This explains the choice of the symbol \( \Phi(0) \) in formula (1).

To measure the spectrum of a given source, it has been found to be best if the CSUC, i.e. in fact the 0-1-sequence is cut into segments of equal length. Each of these segments is then Fourier transformed individually. This leads to a number of new - this time complex-valued - segments. After having replaced all of these complex numbers by the square of their moduli, the average is taken over all segments. The final result is then an estimation of the spectrum. An optional smoothing is possible through the application of a moving average over the frequency range. Due to the finiteness of the segment length \( T \), the spectrum will only be determined at frequencies that are multiples of \( 1/2T \).

Some spectra are shown in the following. They have been measured according to the explanation in the preceeding paragraph. Three types of spectra are shown: the first type is of a TV codec, the second is from a source with exponentially decreasing autocovariance function and the last is of uncorrelated Bernoulli traffic.

Fig. 5 shows the three spectra from a TV source. The three spectra stem from three different TV scenes with different amount of movement which have been coded with a video codec able to compress redundant data. Characteristic for these spectra is that they are almost

\(^3\)In the graphics, the spectrum is always shown over the whole interval \([-1/2,+1/2]\) for any but aesthetic reasons.
constant with the exception of position 0, where they have a profound gap. Their granularity is close to 0 and hence the source belongs to the class of thin traffic which is more or less harmless in terms of buffer occupancy.

Fig.5: Spectra of a video source

The next two spectra (Fig.6) are of a theoretical 2-state Markov source which is a source with exponentially decreasing autocovariance function.

Fig.6: Spectra of a 2-state Markov source.

The structure of a 2-state Markov source is given below.

```
0 ---p----> 1
1-p   q   1-q
```

At each clock pulse, there is a transition (may be from a state to the same state) with the given probabilities. If the chain reaches state 0, the next slot leaves empty, if it reaches state 1, a cell is transmitted. The 2-state Markov source is very interesting because many of the problems in the context of this paper can be solved analytically with this "source". The following formulae show this:

\[
\lambda = \frac{p}{p+q} \quad \sigma^2 = \frac{p_1}{(p+q)^2} \\
N^2 \sigma^2 = \sigma^2 \frac{2\alpha^{N+1} + N(1 - \alpha^2)}{(1 - \alpha)^2} - 2\alpha \\
\alpha(0) = \sigma^2 \frac{1 + \alpha}{1 - \alpha} \quad G = \frac{1 + \alpha}{1 - \alpha} \\
\alpha(t) = \sigma^2 \frac{1 - \alpha^2}{1 + \alpha^2 - 2\alpha \cos(2\pi t)}
\]

where \( \alpha = 1-p-q \). The two spectra belong to the parameter settings \( p=q=0.400 \) (curvature upwards) and \( p=0.666 \) (curvature downwards).

Fig.7: Spectrum of an uncorrelated source

There is no correlation. It corresponds to the special case of the 2-state Markov source for \( \alpha=0 \), i.e. \( p+q=1 \).

As pointed out in the beginning of this chapter, the spectrum serves as "data-base" for the search of a third traffic characterization parameter. This paragraph gave only an introduction the notion of spectrum in the field of ATM traffic. The extraction of a third parameter, however, remains an open issue.

6 Equivalent Offered Traffic

To characterize traffic through the statistics of the iCAR and/or the granularity, resp. the spectrum, is useful
for theoretical and simulation studies. In terms of the criteria presented in section 2 they are not of great help. The statistics of the iCAR may yet be simple enough to be known or measured by the TE, but for the granularity and the spectrum this is no more the case. Concerning the accuracy it must be pointed out that these traffic characterizers seem to be strong enough to estimate the CLR rather accurately; only, there is no general formula that would be simple enough to be implemented. Finally, being statistical quantities, they are not correctly policable. Therefore, it is necessary to find a practical traffic characterizer that 1) can be motivated by the previous chapters, and 2) fulfills the stated conditions.

This section proposes such a traffic characterizer, called the Equivalent Offered Traffic (EOT). The principal idea can be explained using the model of a leaky bucket. In the traditional approach, the leaky bucket is used to police the mean cell rate. To this end, the leak rate is equated with the mean cell rate and the number of credits is determined according to the burstiness. The problem with this approach is that it may react too slowly in order to really protect the network, because of too many credits that allow long bursts to pass the leaky bucket until the first cell is discarded.

In the approach proposed here, two things change with respect to the classical approach: 1) the number of credits \( V \) must be chosen such that a protection of the network can really be guaranteed, and 2) the leak rate is not necessarily equal to the mean cell rate. The leak rate will be fixed above the actual mean cell rate such that a fictitious leaky bucket with the given number of credits would allow the source’s cell stream to pass without discarding cells. The smallest leak rate with this property is called Equivalent Offered Traffic (EOT). In fact, the contract parameters will be exactly the parameters of the policing function, i.e. those of the leaky bucket.

The idea of the EOT relies on the following lemma. It is shown for the case of two inlets, but it can be generalized easily to any number of inlets:

**Lemma L1:** Be \( L(n) \) the number of cells in the output system (=buffer+server) at the beginning of slot \( n \), and \( C_i(n), i=1,2 \), the counter contents of the fictitious leaky buckets at the beginning of slot \( n \). Then

\[
L(n) \leq C_1(n) + C_2(n) \tag{2}
\]

Find the proof in the appendix. Under the condition that the contributary cell processes are stationary, the general form of this lemma reads as

\[
L \leq C_1 + C_2 + \ldots + C_m \tag{2}
\]

or in terms of probability

\[
\text{Prob}[L>s] \leq \text{Prob}[C_1+C_2+\ldots+C_m>s] \tag{3}
\]

The left hand side of (3) is called the buffer congestion probability, where \( s \) is the buffer capacity.

If now the number of credits \( V \) is chosen equal to \( s/m \), and the leak rate equal to the corresponding EOT, then one has from the definition of the EOT:

\[
\text{Prob}[C_i\geq s/m_i] = 0 \quad \forall i \tag{4}
\]

This entails through (3)

\[
\text{Prob}[L>s] = 0
\]

The theory developed up to now allows the conception of a load control algorithm. One possibility is presented in the next chapter.

7 Conception of a Load Control

Any load control algorithm depends on the system and its parameters. In the context of this paper the important parameters are the buffer capacity \( s \) of the switch's output and the buffer congestion probability \( B \). Both parameters are given by the network resp. its operator. Possible values are 256 for the capacity and \( 10^{-10} \) for \( B \). With the use of the EOT, the CAC can be conceived in form of the well known linear algorithm: as the EOTs of the already established connections are known and the EOT of the requesting one is supplied by the TE, the CAC has only to add them and to compare the result with the output rate (normally 1 \( E \)). If the sum of all EOTs is less than the output rate, the new connection can be accepted, otherwise not.

How has the number of credits to be determined? For the system under consideration, where there are buffers only at the individual outlets, the number of credits is equal to the capacity of the output buffers divided by the number of inlets. In a 4-to-1 multiplex with an output buffer of capacity 64 for instance, the number of credits is 16. For other switch architectures, the parameter \( V \) has to be determined differently. It may be possible to “translate” a given architecture to an equivalent output buffered switch. For the moment, this is an open issue.

For source policing, the classical device of a leaky bucket is used. The number of credits is, naturally, determined by the system and the leak rate is equated with the EOT layed down in the contract. It is easy to see that in this way the EOT can be policed to 100%, i.e. there is no arbitrariness as security factors or the like and it reacts at the very moment when a TE is violating the contract.

Simulations have been made to show the effectiveness of this approach (cf. table on next page). An n-to-1 multiplex with an output buffer capacity of 64 was simulated. Depending on the number \( n \) of connected sources, the virtual buffer capacity (and therefore the number of credits) was 64/n for each inlet. At each inlet there was exactly one single source connected, i.e. no multiple sources were used. In principle, for each source
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the EOT should have been determined according to the number of credits. The determination of the EOT, however, is an open issue and therefore the reverse way has been chosen: as a priori arbitrary traffic generator generates a primary cell stream that is shaped by a leaky bucket with a given number of credits and a given leak rate $\lambda_{LB}$. An ensemble of a generator and a leaky bucket constitutes so one source. In this way one can be sure that the EOT of the produced cell stream is equal to $\lambda_{LB}$.

8 Simulation Results

Twenty-eight simulations have been made with different experimental set-ups. Two-state Markov chains were used as primary traffic generators (determined by the parameters $p$ and $q$) which were injected into a leaky bucket with the parameters given in the columns "Credits" and "Leak Rate". The leak rate corresponds then to the EOT of the source in question. The second column (\#Inlets) gives the number of sources that have been connected simultaneously to the multiplex. The results are given in the last five columns: "OT per Inlet" gives the offered traffic per source, "Peak(64)" is the peak cell rate for an integration interval length of 64, "Phi(0)" and "S" estimate the timescale parameter and the granularity of the sources' output (the estimations are not very reliable but give in any case a useful approximation), and the last column "Lmax(#)" indicates the maximum occupancy of the output buffer in a simulation of ten million slots: 63(2) for instance (cf. 1st experiment) means that the maximum buffer occupancy was 63 and that this occurred twice during ten million slots.

What conclusions can be drawn from the results? First it must be pointed out that there have been no cell losses at all, for all maximum buffer occupancies are less than 64. On the other hand, the fact that in a couple of experiments (1, 6, 10, 16, 17, 22, 23) almost all buffer places have actually been occupied means that the values of the EOTs are not too conservative and that a CAC based on this approach would not reject connections wrongly.

It can be seen that the peak cell rate is in almost all experiments approximately the double of the EOT. This means that in the average twice as much connections would be accepted as in a peak cell rate allocation scheme. There is thus a multiplexing gain of about 100%. The EOTs are not too conservative and that a CAC based on this approach would not reject connections wrongly.

It must be repeated that the TE does not have to shape his traffic with a leaky bucket. If the number of credits available is rather small, it has to increase the value of the EOT until the number of available credits suffice for the traffic pattern. If this EOT value is well chosen, any source policing based on a leaky bucket cannot harm the produced traffic. If, however, the EOT declared is too small, the policing will take measures within an appropriate delay that is short enough to guarantee a protection of the network.

9 Summary and Conclusions

This paper comprises two parts. In the first part, parameters for the theoretical characterization of ATM traffic are derived. Besides the well known statistical quantities of the instantaneous CAR, new parameters like the timescale, the granularity and the spectrum are introduced. These parameters have been motivated by a close look to the buffer behaviour under different arrival patterns. They are useful for theoretical and simulation studies. The spectrum for instance is very useful for traffic modelling where a given traffic has to be fitted on a simpler traffic model. A fit is a procedure that adjusts the parameters of the traffic model so that an objective function that measures the deviation of the given traffic from the model, becomes minimum. For studies of the cell loss rate, it is now evident that the spectrum plays a predominant role and it can therefore be used to define such an objective function.

The second part proposes a traffic characterizer, called the equivalent offered traffic (EOT). It has several advantageous over the characterizers proposed up to now: it is simple, allows linear and therefore fast and easy CAC, it can be policed and achieves a zero cell loss rate. This observations have been assessed by two dozen simulations of each ten million slots under very different traffic loads.

Appendix

Proof of $L_1$: $L(n)$ obeys the following recurrence relation:

$$L(n+1) = \max(L(n) + A(n) - 1, 0)$$

where $A(n) = A_1(n) + A_2(n)$ is the number of cells arriving during slot $n$. The counter contents $L_1$ of the fictitious leaky buckets follow a similar recurrence relation:

$$C_i(n+1) = \max(C_i(n) + A_i(n) - \text{EOT}_i, 0) \quad i=1,2$$

The proof is done by complete induction. By putting $L(1) = C_1(1) = C_2(1) = 0$ the lemma is true for $n=1$. Be then $L(n-1) \leq C_1(n-1) + C_2(n-1)$

$$\Rightarrow L(n-1) + A(n-1) \leq C_1(n-1) + C_2(n-1) + A_1(n-1) + A_2(n-1)$$

if the sum of all EOTs is smaller than one, this leads
L(n) + A(n) - 1 ≤ C1(n) + C2(n) + A1(n) + A2(n) - EOT1 - EOT2

By the fact that max(.,0) is an isotone function one has
L(n) ≤ max(C1(n-1) + C2(n-1) + A1(n-1) + A2(n-1) - EOT1 - EOT2,0)

The function max(x,0) is equal to (x+|x|)/2 and this engenders the validity of the triangle inequality for max(x,0). Therefore:
L(n) ≤ max(C1(n-1) + A1(n-1) - EOT1,0) + max(C2(n-1) + A2(n-1) - EOT2,0)

or
L(n) ≤ C1(n) + C2(n)