TRAFFIC CONSIDERATIONS FOR THE PERFORMANCE EVALUATION OF THE ATM NETWORKS

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0. Abstract

In this work, a survey of queuing models is presented with aim to estimate the most important measures such as the cell loss probability and the queue length distribution, resulting from the statistical multiplexing of an ATM switch. In most practical cases the resulting models are complex to implement and require significant amount of CPU time to execute. As it appears, a further research is necessary with aim of getting better idea of the accuracy of the complementary virtual waiting time distribution.

1. Introduction

Asynchronous Transfer Mode (ATM) is the most promising proposed standard for Broadband Integrated Services Digital Networks (B-ISDN). It is designed to transport all types of traffic streams (voice, video, data) with various traffic characteristics and different performance requirements. Adaptation types and quality of service (QoS) parameters are designed to suit a broad range of user requirements for service, involving multiple media. Thus, a source of traffic (or a user) negotiates at connection set-up a traffic contract, which includes traffic characteristics and requested QoS. The network is obligated to serve the client via specific Virtual Path / Channel Connections (VPC/VCC), guaranteeing a specific service scheme, that when the user follows, do not have cell losses.

The current tendency has led scientists to consider a certain number of transfer capabilities, so as to define the traffic parameters which are to be declared by a connection, the type of QoS guarantees provided, and a conformance definition. Four ATM service classes have been proposed: Deterministic Bit Rate (DBR), Statistical Bit Rate (SBR), Available Bit Rate (ABR), and Unspecified Bit Rate (UBR). In DBR capability resources are allocated on the basis of the declared Peak Cell Rate (PCR) and strict QoS guarantees are given, e.g. the Constant Bit Rate (CBR) sources like 64 Kbps telephone voice transfer. SBR capability is based on a statistical multiplexing capability with QoS guarantees used by Variable Bit Rate (VBR) sources like video image transfer. The resources are allocated on the basis of an estimate of the peak and mean cell rate and a maximum burst size. The ABR capability is intended for data sources (e-mail, file transfer, etc.) with relatively loose delay constraints, providing no guaranteed bandwidth to the user. However through ABR service the network provides a 'Best Effort' service, in the sense that no hard QoS guarantees are given, but the network does its best to minimize cell loss and delay. A minimum cell rate is guaranteed under the condition that the connection respond to congestion feedback indications from the network. Finally the UBR capability is designed for those data applications that want to use any left-over capacity and are not sensitive to cell loss, or delay. Such connections are not rejected in the basis of bandwidth shortage (no traffic contract); their sources are not expected to reduce their cell rate, and their cells during congestion are lost (e.g. e-mail, news feed, etc.).

The problem of traffic control in ATM networks, namely the capability to monitor and regulate traffic flows, has been widely recognized for a long time. Over the past two years a consensus on the basic principles of traffic control has slowly emerged within the industry. ITU-T Recommendation I.371, was an attempt to formulate a general outline of traffic control principles and functions. Work is continuing on the details of specific control mechanisms and procedures. In this respect, traffic characteristics are currently defined using the Generic Cell Rate Algorithm (GCRA), also called Continuous State Leaky-Bucket, or Virtual Scheduling Algorithm (VSA), that has been proposed by the ATM Forum as a reference model to define certain parameters of a cell stream.

In this work we only consider at traffic parameters that are negotiated at call set-up, that are not negotiated during the connection life-time and that are controlled at the ingress of the ATM network. These parameters define the so called open-loop control, which correspond to either the DBR or the SBR transfer capabilities. Thus, using GCRA terminology, DBR connections are described in terns of GCRA(T, $\hat{o}$), with $1/T$ the PCR and $\hat{o}$ the Cell Delay Variation Tolerance (CDVT). It relates a time period value, namely, the inverse of a cell rate value, with a tolerance value that quantifies the maximal deviation of the considered cell stream from a purely periodic behavior. For SBR connections a further mechanism is necessary, namely the GCRA(T_{SCR} , $\hat{o}_{IBT}$), where $\hat{O}_{SBR}$ is the VC sustainable cell rate and $\hat{o}_{IBT}$ is the Intrinsic Burst Tolerance (IBT). These two mechanisms will operate in a coordinated fashion.

Many traffic parameters are compatible with a rule-based descriptor of given parameters. A straightforward and safe approach is to allocate resources based on the so called Worst Case of Traffic (WCT) corresponding to the traffic descriptor parameters submitted by the VC. Therefore we focus on the resource allocation policy based on deterministic traffic patterns that are used as worst case sources at the output of the conformance mechanism. The paper is organized as follows. In section 2 we describe the traffic characterization, while in the section 3 we discuss the Beneš results for the WCT of the DBR connections. Further, in section 4, we examine the problem of DBR sources with CDVT. Finally, in section 5 we summarize the results.

2. Traffic Characterization

The GCRA has been proposed as a reference model to define certain parameters of a cell stream, that are useful for connection set-up. The algorithm involves two parameters (an increment T and a limit τ), and it is denoted by GCRA(T, τ). It can be explained by either of two equivalent versions; a VSA and a continuous state leaky bucket algorithm. However, in the following we limit our interest in the first version, the second has been discussed in [7] and [8].

In the VSA the actual arrival time of the k^{th} cell, say ta_k, is compared with its theoretical arrival time, say TAT_k, which is the expected arrival time under the assumption that cells are all spaced equally in the time with distance T. The algorithm is intended to ensure that the cell rate is not greater than $1/T$ on the average, with some tolerance dependent on τ; that is cells will not arrive too much earlier than their theoretical arrival times. More precisely, the k^{th} cell is conforming the pair (T, τ) if and only if $ta_k > TAT_k - \tau$; otherwise, it is non conforming (too early). The theoretical arrival time for the next cell, TAT_{k+1}, is calculated as a function of ta_k. If the k^{th} cell is conforming and $ta_k < TAT_k$, then the next theoretical arrival time is set to $TAT_{k+1} = TAT_k + T$. If the cell is conforming and $ta_k \geq TAT_k$, then the next theoretical arrival time is set to $TAT_{k+1} = ta_k + T$. Note that non conforming cells are not counted in the update of the theoretical arrival times. Therefore, TAT_{k+1} is described as a function of ta_k, as follows:

$$TAT_{k+1} = \begin{cases} TAT_k + T & if \quad 0 \leq TAT_k - ta_k < \tau \\ ta_k + T & if \quad TAT_k - ta_k < 0 \\ TAT_k & if \quad TAT_k - ta_k > \tau \end{cases}$$

The definition of cell conformance given above has a close relationship to a single server queue model with deterministic service time (see table 1). For example, the set of actual arrival times $ta_k ; k \geq 0$, define a general arrival process to a virtual deterministic queue whose service duration is T. Further, the set of theoretical times $TAT_k ; k \geq 0$, that are computed recursively, represent the virtual departure times from the virtual simple server queue. Clearly, TAT_k represents the departure time of cell *k-1* from the so defined virtual *G/D/1* queue. In the *G/D/1* model, if the virtual waiting time $W_k = TAT_k - ta_k$ is negative, the user corresponding to cell *k* initiates a busy period in *G/D/1* queue and $ta_k - TAT_k$ is the duration of the idle period that is terminated by the arrival of cell *k*. If W_k is non-negative, it represents the waiting time of the customer corresponding to cell k in the *G/D/1* model.

A given cell is considered as conforming, namely the user in the corresponding queuing model is not rejected, if and only if the virtual waiting time in the *G/D/1* model, ($W_k = TAT_k - ta_k \leq \tau$) is limited by τ. If τ is an integer multiple of *T*, the corresponding *G/D/1* queue is finite of capacity τ/T. Thus, the maximum number of conforming cells accessing the conformance procedure at link rate is $B_c = 1 + \lceil \tau/(T-1) \rceil$, where *T* and τ are expressed in cell unit times (a cell unit time is the time needed to transmit a cell at link rate), and assuming that only one cell access the conformance procedure per cell unit time.

3. Beneš results for *G/D/1* systems

The QoS measures we are interested in, are in particular the stationary cell loss probability and/or the queue length distribution. In a Connection Acceptance Control (CAC) context, we are ultimately interested in assessing the maximum acceptable number of sources for a given cell loss probability (P_{loss}), namely the proportion of cells finding a full buffer upon arrival. The analysis considered here is based on systems with constant service time and infinite buffer size namely the proportion of cells finding a full buffer upon arrival. Thus, the classical Beneš result applied to *G/D/1* systems and given by $Q(x) = \sum_{n>x} Pr\{A_{n-x} = n \wedge W_{t-x} = 0\}$, may be applied. In the above it is assumed that the system is observed at time 0, A_t is the number of cell arrivals in (-t, 0), and $Q(x) = Pr\{W_t > x\}$ denotes the complementary distribution of the unfinished work (virtual waiting time). This result is very general and allows in theory, the computation of the unfinished work W_t. However, an exact analysis is quite difficult and so approximations are necessary. Note that, if X_t presents the number of cells in the system, then $X_t = \lfloor W_t \rfloor$, and thus $Q(x) = Pr\{W_t > x\} = Pr\{X_t > x\}$, where *x* is an integer. In discrete time systems with finite buffer capacity equal to K cells, the cell loss probability is related with the tail distribution $Q(x) = Pr\{W_t > K\}$ through the relation $P_{loss} \leq Q(K)/\rho$ [14]. Another bound is provided by [10], where it is stated that:

$P_{loss} \leq \left\{ Pr\left\{ X_t \geq K \right\} - Pr\left\{ X_t^K = K \right\} \right\} \big/ \rho$, where $Pr\left\{ W_t^K = K \right\}$ is the congestion probability and ρ is the link utilization factor. Note that, in general, the tail approximation $P_{loss} \approx Pr\{X_t > K\}$, strongly depends on the load. Thus, the relation $Pr\{X_t > K\} > P_{loss}$ is true only for $\rho > 0.5$, while at small load the tail approximation underestimates the P_{loss} . Further, under heavy load the tail approximation considerably overestimates the buffer size necessary to achieve a given P_{loss}. For the systems under study the approximation $P_{loss} \approx \left(1-\rho\right)Q(K)\big/\rho$, has been proposed ([2]). However the validity of the approximation has to be demonstrated for more general cases and in particular when extending order relations from infinite to finite buffer systems.

In the following we review the $\sum_i N_i * D_i / D/1$ queuing system and its variations for which no exact analytical model exists. The sources are assumed independent to emit a cell every D_i time units. All the randomness in these models is contained in the phases of the different sources which phases are assumed to be uniformly distributed over the source period.

3.1 The homogeneous *N*D/D/1* infinite buffer model.

In the homogeneous *N*D/D/1* model ([11], [12]) there are N independent sources, each one of which emit one cell per D time units. The parameter D corresponds to the traffic descriptor T, normalized by the service time of the ATM cell. The parameter τ is not considered in the model since CDV tolerance is assumed to be small. This model is appropriate to study the multiplexing of N homogeneous sources which conform strictly to their PCR. Under the assumption that the system is observed at time 0 and that N<D, namely the system is empty at some instant at (-D, 0), the Beneš result may be applied to the *N*D/D/1* model, giving the following exact formula for the function *Q(x)*:

$$Q(x) = \sum_{x<n\leq N} \Pr\left\{ A_{n-x} = n \right\} \Pr\left\{ W_{t-x} = 0 \middle| A_{n-x} = n \right\}, \text{ or}$$

$$Q(x) = \sum_{x<n\leq N} \binom{N}{n} \left(\frac{n-x}{D} \right)^n \left(1 - \frac{n-x}{D} \right)^{(N-n)} \left(\frac{D-N+x}{D-n+x} \right).$$

Note that *Q(x)* has the same distribution as if the arrival process were just *N* arrivals uniformly distributed over (*-D, 0*). The above result can be readily implemented on in a computer. However, for a large number of sources the calculations may require considerable CPU time, because *Q(x)* has complexity $O(N^2)$.

3.2 The homogeneous finite buffer case *N*D/D/1/K*, queuing analysis.

The results for this system have been summarized in [11]. Depending on the overload situation different algorithmic approaches are applied. Thus, in case $N<D$ the loss probability can be calculated by means of the following recursive relation [1]:

$$P_{loss} = \sum_{l=0}^{K} \sum_{m=l}^{N-1} \frac{(m-l) q_{N-1,D}(m)}{m+1} P_{N-m-1,D-1}(K-l),$$

where $q_{N,D}(m) = \binom{N}{m}\left(\frac{1}{D}\right)^{m}\left(1-\frac{1}{D}\right)^{(N-m)}$, $0 \le m \le N$, is the probability that m cells arrive at the beginning of slot D and

$$P_{N,D}(k) = \begin{cases} \sum_{m=0}^{k+1} q_{N,D}(m) P_{N-m,D-1}(k-m+1), & D \ge 2,\ 1 \le k \le K-1 \\ \sum_{m=1}^{K} q_{N,D}(m) P_{N-m,D-1}(K-m+1) + \sum_{m=K+1}^{N} q_{N,D}(m), & D \ge 2,\ k = K \end{cases}$$

is the probability that the queue length is k at slot D. In the overload case $N>D$, ([5], [6]), a simpler expression is given for P_{loss} in terms of *ö*, namely, the probability that the server is idle. Thus, $P_{loss} = (\tilde{n}-1+ö)/\tilde{n}$, where $\tilde{n}$ is again the load factor N/D. This yields $P_{loss}=(N-D+P_{N,D-1}(0)\, q_{N,D}(0))/D$ an expression which is not very useful for calculating small values for P_{loss}, because a very high accuracy of $\varphi = P_{N,D-1}(0)\, q_{N,D}(0)$ is required. In the overload case and when buffer is small the P_{loss} remains fixed at $P_{loss}=(\rho - 1)/\rho$, since $\varphi=0$.

GCRA(T, τ)	***G/D/1* queue**
***T*: Cell interemission time**	**Duration of service time**
ta_k: Arrival time of cell k	**Arrival time of the k^{th} customer**
TAT_k: Theoretical arrival time for cell k	**Departure time for $(k-1)^{th}$ customer**
Cell *k* conforming and $0 \le TAT_k - ta_k \le \tau$	**$W_k=TAT_k - ta_k$; waiting time for cell k**
Cell *k* conforming and $TAT_k - ta_k < 0$	**k^{th} arrival initiates a busy period**
Cell *k* non-conforming $TAT_k - ta_k > \tau$	**k^{th} customer rejected**
$\left\lceil \frac{TAT_k - ta_k}{T} \right\rceil$	**Number of cells in buffer at time ta_k**

Table 1. Relationships between GCRA(*T, τ*) algorithm and *G/D/1* queue model

3.3 The $\sum_i N_i * D_i / D/1$ system.

This system is a special case of the $\sum_i D_i / D/1$ system and due to its complexity very few exact analytical models exist . Therefor one must rely only on approximations. However, an exact solution for $Q(x)$ may be obtained in the case $N<D$, where $D = min\{ D_i \}$ is the shortest of the

periods in the superposition. An accurate expression for the complementary distribution $Q(x)$ is given by ([12]):

$$Q(x) \le \sum_{n>x} \left\{ \frac{\prod_i (1+r_i z_n - r_i)}{z_n - \sum d_i} \frac{1}{\sqrt{2\pi}\sigma_n} \left(1 - \sum_i \frac{1}{D_i (1+r_i z_n - r_i)} \right) \right\},$$ where z_n is the root of

$$\sum_i \frac{r_i z}{(1+r_i z - r_i)} = n - \sum_i d_i \quad \text{and} \quad \sigma_n^2 = \sum_i \frac{r_i (1-r_i) z_n}{(1+r_i z - r_i)^2}.$$

However simple, upper and lower virtual waiting time bounds can be found. These bounds are moderately accurate and their complexity is in $O\left(\left(\sum N_i\right)^3\right)$.

A WCT for the $\sum_i N_i * D_i / D/1$ model, is obtained by, the homogeneous $N*D/D/1$ system, with $\rho = \sum (N_i / D_i)$ and $D=max\{ D_i \}$, as it has already been described in subsections 3.1 and 3.2 above.

4. PCR allocation for DBR sources with CDV

In this casewe will consider models for which sources declare a CDV tolerance $\tau > T-1$ yielding a WCT. The simplest case is the homogeneous $N*WCT/D/1$ model for which each source emits a periodic cell stream of period D, first emitting a burst of b back-to-back cells at the multiplex rate of length equal to the Maximum Burst Size $b = MBS = \lfloor 1+ \tau/(T-1) \rfloor$ slots and followed by a silence of $SL = D - b$ slots. The time slot at which a source 'awakes' is uniformly distributed over the period, while for stability it is assumed $N*b/D<1$. Approximate methods to solve the above system may be found in [3]. However, an analytical solution giving a closed form expression for the $Q(x)$ is provided by [4]. A review of this method follows.

Let N_t denotes the number of cell arrivals during (-t, 0), $ö(t) = N_t - t$ defines the excess work and W_t is the virtual waiting time at time $-t$. Further let us define by ã$_t$ the number of active sources at time -t, $\hat{a}_t$ is the number of sources becoming active in $(-t, 0)$. Then by conditioning on having no active sources at time $-t$ and i sources becoming active in $(-t, 0)$, we obtain:

$$Pr\{W_0 > x\} = \sum_{t=1}^{D} \sum_{i=1}^{N} Pr\{\varphi(t) = x, \gamma_t = 0, \beta_t = i\} \cdot Pr\{\varphi(u) < x,\ t < u \le D \mid \varphi(t) = x, \gamma_t = 0, \beta_t = i\}$$

Note that a simple closed form for the above joint probability is provided in [9].

Thus $Pr\{\varphi(t) = x, \gamma_t = 0, \beta_t = i\}$ can be expressed as:

$$\begin{cases} \binom{N}{i} \dfrac{t^i (D-b-t)^{N-i}}{D^N} \dfrac{1}{t^i} q_t^{(i)}(t+x), & \text{if } 1 \le t \le b-1 \\ \binom{N}{i} \dfrac{t^i (D-b-t)^{N-i}}{D^N} \sum_{j=0}^{i} \binom{i}{j} \dfrac{(t-b+1)^i}{t^i} q_{b-1}^{(i-j)}(t+x-bj), & \text{if } b \le t \le D-b \\ \dfrac{t^N}{D^N} \sum_{j=0}^{N} \binom{N}{j} \dfrac{(t-b+1)^j}{t^N} q_{b-1}^{(N-j)}(t+x-bj), & \text{if } D-b+1 \le t \le D,\ i=N \\ 0, & \text{if } D-b+1 \le t \le D,\ i<N \end{cases}$$

while, $Pr\left\{\varphi(u) < x,\ t < u \le D \mid \varphi(t) = x, \gamma_t = 0, \beta_t = i\right\} = \left(1 - \dfrac{(N-i)^b}{D-t}\right) \Big/ \left(\dfrac{D-t-b}{D-t}\right)^{N-i}$

As it appears, the complexity of the analytical solution for the *N*WCT/D/1* model increases in the heterogeneous case. For this model only the special case of two source types with bursts of different length and common period D has been solved [4]. Further the link between *Q(x)* in the *N*WCT/D/1* system and P_{loss} in the corresponding finite model has not been investigated so far.

5. Conclusions

In this paper we have provided a survey of some queuing models used to estimate the P_{loss} in an ATM network having a single switch, with multiple VPC/VCC, that carry DBR traffic. Our intent was to study the complexity. It appeared that more work has to be done in order to produce tractable analytical models in terms of computational complexity and CPU time required particularly when the number of links is large.

6. References

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