Methods for UPC dimensioning of a CDV perturbated cell stream

Søren Blaabjerg[1] and Sándor Molnár[2]

Abstract

This paper discusses the influence Cell Delay Variation (CDV) has on the peak rate enforcement in ATM networks. Three different models for the setting of the peak cell rate and the CDV tolerance are presented and evaluated in the case when the access (or upstream) network can be modelled as a single FIFO queue. The case in which the access network is a tandem of queues with interfering traffic is considered in the two special cases of heavy and light load.

1 Introduction

In the first generation ATM systems, bandwidth allocation will be done according to the peak cell rate of the connections. Proper Usage Parameter Control (UPC) of the peak cell rate is made difficult because the cell stream of a typical ATM connection is multiplexed and switched with other cell streams in the access network before entering the UPC device and it is switched and multiplexed in various network elements in one operators network before entering the Network parameter control (NPC) device at the entrance to the next operators network. Thereby cell delay variation (CDV) is introduced.

In order to have a consistent definition for conformance testing as well as a feasible way to avoid compliant traffic sources from suffering from excessive cell discards in the UPC/NPC mechanism due to the introduction of CDV it has been necessary to characterise the peak cell rate of an ATM connection by two parameters, see [14] and [1]:

- The peak emission interval T, which is the distance between two adjacent cells of the connection transmitted at peak rate. Equivalently $1/T$ is the peak cell rate of the connection.
- The CDV tolerance τ. τ is the threshold value in a continuous state leaky bucket with leak rate $1/T$. τ is to be interpreted as a measure of the amount of cell delay variation which is allowed to be introduced in the access network.

The objective of this paper is to describe a number of methods, developed mainly in the COST 242 project (see [8]), for the setting of T and τ of a CBR connection for which CDV is introduced in the access or upstream network. Three different methods will be presented.

[1]Institute of Telecommunications, Technical University of Denmark,
DK-2800 Lyngby, Denmark, (e-mail: sbb@it.dtu.dk)

[2]Department of Telecommunications & Telematics, Technical University of Budapest,
Sztoczek u. 2., H-1111 Budapest, Hungary, (e-mail: molnar@bme-tel.ttt.bme.hu)

The first method is a simple method which uses a delay quantile of the variable part of the transfer delay through the access network. It's two main advantages are that it is very simple, and it is valid also in the case where the leak rate is equal to the peak rate of the connection (no over-allocation). The method is applicable both when the access network is a single queue and when it is a tandem of queues. It requires that the transfer delay distribution or some approximation of it is available. To the authors knowledge the method was first published in [20].

The second method approximates the CDV perturbated CBR cell stream by a renewal process, and uses the Kingman bound, see [15] to derive τ and T. This method, which applies to the same scenarios as the above simple method, is very fast, and it requires a transform of the distribution of the time between adjacent cells of the CDV perturbated cell stream. Many contribution in the literature e.g. [2], [12] and [10] have used the renewal approach, but only [16] seem to have used the effective Kingman bound.

The third method only applies to the case where the access network can be modelled as a single FIFO queue. The evolution of the queue length in time is approximated by a reflected Brownian motion and thereby it becomes possible to compute the distribution of the number of arrivals in an arbitrary time interval. With this set of distributions available, the Beneš result for the general single server queue, see section 5 in [7], can be applied to obtain the probability of exceeding the τ value. The approach is described in [3]. The two main advantages of this method are, that it, despite the fact that it appears complicated, is reasonable fast, and it takes the correlation of the underlying CDV affected cell stream into account. The two main disadvantages are that it only applies when the access network can be modelled as one FIFO queue, and it requires knowledge on the superposition of the other cell streams (the background cell stream). This third method has been derived as an approximation of an exact method [11]. However, the exact method requires unreasonable much computational effort to be apply in this context.

In section 2 the equivalence between the algorithmic conformance to the peak cell rate and the unfinished work in the G/D/1 queue is described. Section 3 presents in some detail each of the three methods for setting T and τ. Furthermore, section 3 presents some recent results of how CDV evolves as the number of tandem queues before the UPC/NPC becomes large and the load is either very light or very heavy. Section 4 is devoted to numerical examples, where the focus is on;

- the relative performance of the three methods in the case where the access network is a single FIFO queue with interfering traffic,
- performance in light and heavy traffic when the access network consists of a large number of tandem queues with interfering traffic.

2 Conformance Testing (Modified 1-point CDV) and the G/D/1 Queue

We shall here give the definition of conformance without presenting the (non-modified) 1-point CDV definition first. Readers interested in full details are referred to [13], [14] and section 2.2.1 in [8].

Using the formalism given in I.356, an observed cell is conforming to the pair (T, τ) if and only if its (modified) 1-point CDV value $y'_k := c'_k - a_k$ is smaller than the CDV tolerance τ. a_k

is the actual arrival of cell k and c'_k is the (modified) theoretical time of cell k. For the modified 1-point CDV, the next theoretical time (for cell $\#(k+1)$) is obtained as:

$$\begin{aligned} c'_{k+1} &= c'_k + T && \text{if } \tau \geq y'_k \geq 0 \\ &= a_k + T && \text{if } y'_k < 0 \\ &= c'_k && \text{if } y'_k > \tau \end{aligned} \tag{1}$$

The above definition is valid for any type of connection for which a Peak Emission Interval T and a CDV tolerance τ have been negotiated in the traffic contract. Therefore, it is applicable not only to CBR connection, but to any connection types, since the negotiation of a Peak Cell Rate is mandatory for every connection.

The close relationship between the modified 1-point CDV parameter and the evolution of the unfinished work in the G/D/1 queue is best illustrated in a table as below.

input	1-point CDV	G/D/1 queue
a_k	arrival of cell k	arrival of cell k
c_k	theo. arr. of cell k	depart. time for cell $k-1$
$c_k - a_k$	diff in teo. and act. arr.	wait. time for cell k
$y_k < 0$	cell k late	cell k starts busy period
$y_k > \tau$	cell k non conforming	cell k arrives at full buffer
$\lceil \frac{c_k - a_k}{T} \rceil$	amount of clumping	number in buffer at time a_k

As the figure shows then the modified CDV value y'_k is the unfinished work in the queue when cell k arrives to the system.

3 Models and Methods for the Setting of Peak Cell Rate and CDV Tolerance

Here the three different methods mentioned in the introduction will be presented in more details. First, a short subsection on assumptions and notation is needed.

3.1 Assumptions and notations

A CBR source is emitting cells periodically with interarrival time T_{CBR}. The cells are passing an access network before entering the conformance testing device. For principial reasons we destinguish between *conformance testing* and *UPC/NPC enforcement*. The conformance testing algorithm is standardized, it is called the Generic Cell Rate Algorithm (GCRA), and therefore known. This is not the case for the UPC/NPC algorithm even though most (if not all) vendors for obvious practical reasons will implement the generic cell rate algorithm (GCRA) as the UPC/NPC algorithm.

The access network will consist of either a single FIFO queue in which the CBR cell stream is multiplexed with a background cell stream, or it will consist of a sequence or tandem of queues and in each queue the CBR cell stream is multiplexed with a new background stream which immediately after the queue leaves the system.

The variable part of the delay of CBR cell no. n between the source and the entrance of the GCRA is denoted W_n. The time between CBR cell n and CBR cell $n+1$ at the GCRA is called the *inter-departure time* (departure from the accesss network) and its distribution is denoted F_n. Subscript n is often suppressed when the sequence is assumed stationary.

The objective of each of the three methods is, given the peak emision interval T to find the CDV tolerance τ such that the probability of declaring a cell non conforming is kept less than a given threshold, typically 10^{-9} or 10^{-10}.

3.2 A Quantile of the Transfer Delay Distribution

Consider a CBR source for which interarrival time T_{CBR} is chosen equal to the peak emission interval T. Consider the modified 1-point CDV definition and let cell no. 0 initiate a busy (clumping) period. Choose time 0 as the time when cell 0 is emitted from the source. Assume further that cell k is within the same busy period and that no cells up to cell k is declared non conforming. Then $c_0 = a_0 = D + W_0$, $c_k = D + c_0 + kT$ and $a_k = kT + W_k + D$ where D is the deterministic part of the delay from the source to the GCRA. Then

$$c_k - a_k = W_0 - W_k \leq W_0. \tag{2}$$

Based on this it can be seen that a simple worst case dimensioning of τ in case of critical allocation $T_{CBR} = T$ (no over-allocation) is the 10^{-r} quantile of the W distribution i.e.

$$\tau = \inf\{t > 0 | P(W > t) \leq 10^{-r}\} \tag{3}$$

In case of over-allocation ($T_{CBR} > T$) the same bound is being applied as a worst case. Note however, that no strict proof that the ratio of non-conforming cells is upper bounded by 10^{-r} seems to exist.

3.3 Approximating the CDV perturbated Stream by a Renewal Process

In this method it is assumed that it has been possible by some means, either measurements, simulations or in some limited cases by a detailed analytical model like [11], [18], or [3] , to find the inter-departure time distribution between adjacent CBR cells. By assuming that individual inter-departure times are mutually independent, the CDV perturbated CBR cell stream is approximated by a renewal process (GI stream). Applying the equivalence between the conformance algorithm and the single server queue we may approximate the fraction of non-conforming cells with the probability that the waiting time in the GI/D/1 queue exceeds τ.

An exact analysis of the GI/D/1 queue is in general difficult unless the inter-departure[3] time has a Coxian distribution. Instead we shall, as done in [16], apply the Kingman bound, which states

$$P(W > x) \leq e^{-s_0 x} \tag{4}$$

where $P(W > x)$ is the probability that the waiting time exceed x, and where $s_0 = \sup\{s > 0, F^*(s)e^{sT} \leq 1\}$ with F^* denoting the Laplace Transform of the inter-departure time distribution. For further detail we refer to [15] and section 2.4 in [17].

Let 10^{-r} denote the maximum allowed ratio of non-conforming cells. Then $\inf\{x > 0 | P(W > x) \leq 10^{-r}\} \leq \inf\{x > 0 | e^{-s_0 x} \leq 10^{-r}\}$ and as the dimensioning criteria we use

$$\tau = \frac{r ln(10)}{s_0} \tag{5}$$

see also section 7.1.2 in [8].

[3] in a typical queueing context, normally called the interarrival time

3.4 Modelling the Evolution of Virtual Waiting time by a Diffusion Process

Assume the access network is modelled as a discrete time FIFO queue in which the CBR stream under investigation is multiplexed with a background cell stream. Assume the background stream is submitting cells in independent and identically distributed batches in each time slot. This model is normally denoted $GI^{[X]} + D/D/1$ and it is possible to formulate and solve it in an exact way, see [11] and [5]. However, the computational burden in the specific application to be set up here is very high and we prefer to present a computational simpler model which offers the same basic qualities as the exact model.

In the approximate model the evolution of the queue length (or virtual waiting time) between CBR arrivals is modelled by a reflected Brownian motion with drift m (m assumed smaller than zero in order to ensure a stable queue), variance σ^2 and a reflection in zero. Let $\tilde{W}_t$ denote the unfinished work in the diffusion queue at time t. The waiting time of CBR cell no. n, is approximated by:

$$W_n = \tilde{W}_{nT} \tag{6}$$

that is *the waiting time that CBR cell no. n experience in the queue is approximated by the virtual waiting time in the diffusion queue at time nT.*

Both the arrivals of the CBR cells as well as the cells from the background process are modelled in accordance with the diffusion approach i.e CBR arrivals as well as background arrivals and departures are taken into account by a proper choice of drift $m$as well as variance σ^2in the diffusion process.

For the $GI^{[X]} + D/D/1$ queue it can be seen from the Laplace Transform that the queue length has a geometric tail behaviour and that the slope of this tail can be found as the root of a functional equation, see [6]. The diffusion approximation enforces an exponential virtual waiting time and by a careful choice of the diffusion variance it is possible to match these two asymptotic behaviours, see [3] for further details. The diffusion drift m is chosen as $m = \rho - 1$ which is standard.

The computation carried out in [3] shows that the time dependent shifted inter-departure time[4] distribution function is given as:

$$\tilde{F}_n(x) = P\{\tilde{U}_{nT_{CBR}} \le x\} = \begin{cases} \frac{1}{2} + \frac{1}{2}\Phi(\frac{x - mnT_{CBR}}{\sigma\sqrt{nT_{CBR}}}) - \frac{1}{2}e^{2\frac{mx}{\sigma^2}}\Phi(-\frac{x + mnT_{CBR}}{\sigma\sqrt{nT_{CBR}}}), & \text{for } x \ge 0 \\ \frac{1}{2}e^{-\frac{2mx}{\sigma^2}}\Phi(\frac{x - mnT_{CBR}}{\sigma\sqrt{nT_{CBR}}}) + \frac{1}{2}\Phi(\frac{x + mnT_{CBR}}{\sigma\sqrt{nT_{CBR}}}), & \text{for } x < 0 \end{cases} \tag{7}$$

where Φ denotes the Gaussian distribution function with zero mean and unit variance. From this expression it is seen that the probability distribution function $\tilde{F}_n$ for $\tilde{U}_{nT_{CBR}}$ fulfil the relation: $\tilde{F}_{nT_{CBR}}(x) + \tilde{F}_{nT_{CBR}}(-x) = 1$, thus implying that the density function for $\tilde{U}_{nT_{CBR}}$ is symmetric.

From the shifted inter-departure time distribution it is possible to find most point process quantities of interest related to the CDV perturbated cell stream including a closed form expression for the distribution of the number of departures in a given time interval, see [3] for details. With these distribution known, we may apply the Beneš upper bound, see section 5.3 in [7], which states

$$P(V > x) \le \sum_{n>x} P\{N((n-x)T) = n\} \tag{8}$$

where V is the unfinished work at an *arbitrary time* (not to be confused with an arbitrary arrival). $N((n-x)T)$ is the number of departures in a time interval of length $(n-x)T$ starting

[4]the inter-departure time with its mean subtracted

at an arbitrary time. With T_{CBR} and T given it is possible by applying the equivalence between the G/D/1 queue and the GCRA to use $P(V > \tau)$ as an approximation for the ratio of non-conforming cells in the GCRA.

3.5 The case with Tandem Queues and Either Light or Heavy Load

In the case where the access network consists of a number of tandem queues, a detailed analysis as the diffusion model becomes infeasible. A simpler but still rather complicated analysis has been performed in [18]. Here the superposition of a renewal stream and a background stream consisting of identically distributed and independent batch arrivals (the $GI+GI^{[X]}/D/1$ queue) has been analysed and the inter-departure time distribution of the renewal stream has been obtained. By assuming it to be renewal at the output the result can be used as input for the next queue in which the same analysis can be performed with the new parameters etc. etc.

Since the analysis is complicated the authors of [18] have derived two simpler models based on their complicated model. One model assumes each queue to be in heavy load ($\rho = 1$), while the other model assumes the traffic of the background to be light.

3.5.1 Tandem Queues in Heavy Load

By assuming heavy load, the event of empty queues can be neglected and applying arguments from the theory of branching processes, [4], or by working with the model of [18], formulas for the generating functions of the inter-departure times after passage of M queues, $M = 1, 2, ..$ can be derived. From these formulas a simple recursive formula for the variance of the inter-departure time at the output of queue M can be found. It says

$$\sigma^2_{M+1} = \sigma^2_M \left(\frac{T_{CBR} - 1}{T_{CBR}}\right)^2 + T_{CBR}\sigma^2_B \tag{9}$$

where σ^2_M is the variance of the inter-departure time distribution at the output of queue M and σ^2_B is the variance of the background batch size distribution.

From formula (9) it can be seen that as the number of queues M approaches infinity, the variance converges to the finite limit $\sigma^2_\infty = \frac{T_{CBR}\sigma^2_B}{1-(\frac{T_{CBR}-1}{T_{CBR}})^2}$. Also the inter-departure distribution converges towards a limit distribution, see [4].

3.5.2 Tandem Queues in Light Load

By Taylor expanding the Generating function of the background batch size distribution around a background load of zero, and applying the model of [18], see [19] for details, the variance of the inter-departure time after passage of queue M in the case of Poissonian background can be approximated by

$$\sigma^2_M = M\rho^2 \tag{10}$$

In the next section the formulas (9) and (10) are applied.

4 Numerical Results

The numerical experiments are divided into two parts. In the first part we investigate the relative performance of the three methods introduced in section 1 by considering the example in which the access network consists of one FIFO queue. In the second part we provide a few numerical examples for the case where the access network consists of a large number of tandem queues focusing on the light load and heavy load case.

4.1 Relative Performance of the Three Methods

The interarrival time for the CBR connection under investigation is chosen to $T_{CBR} = 20$. It passes through an access network consisting of a single FIFO queue in which it is multiplexed with a background stream. The aggregated load on the queue is 0.8. Three different models of the background traffic is considered.

- In case I it consists of 2 Bernoulli streams each with probability $p = 0.375$ of submitting a cell to the present time slot. Thereby the peakedness of the background traffic is 0.625.
- In case II the background stream is a Poisson stream with intensity 0.75.
- In case III the background stream is bursty, here modelled by a negative binomial batch size distribution with peakedness 2 and mean 0.75.

After passage of the FIFO queue the CBR stream is subject to a conformance testing procedure and the objective is to compute the CDV tolerance τ for a sequence of peak emission value T based on the criterion that the probability of declaring a well behaving cell as non-conforming should not exceed 10^{-9}

Table 1 - 3 provides figures of the CDV tolerance τ for the three traffic types.

Table 1: τ as a function of T with binomial background ($T_{CBR} = 20$)

	$T = 19$	$T = 18$	$T = 17$	$T = 16$	$T = 15$	$T = 14$
Simple method	$\tau = 25$	$\tau = 25$	$\tau = 25$	$\tau = 25$	$\tau = 25$	$\tau = 25$
Kingman	$\tau = 32$	$\tau = 20$	$\tau = 16$	$\tau = 13$	$\tau = 11$	$\tau = 10$
Diffusion and Beneš	$\tau = 38$	$\tau = 35$	$\tau = 33$	$\tau = 32$	$\tau = 31$	$\tau = 30$

Table 2: τ as a function of T with Poisson background ($T_{CBR} = 20$)

	$T = 19$	$T = 18$	$T = 17$	$T = 16$	$T = 15$	$T = 14$
Simple Method	$\tau = 45$	$\tau = 45$	$\tau = 45$	$\tau = 45$	$\tau = 45$	$\tau = 45$
Kingman	$\tau = 68$	$\tau = 38$	$\tau = 28$	$\tau = 23$	$\tau = 19$	$\tau = 16$
Diffusion and Beneš	$\tau = 54$	$\tau = 48$	$\tau = 44$	$\tau = 42$	$\tau = 40$	$\tau = 39$

Table 3: τ as a function of T with negative binomial background ($T_{CBR} = 20$)

	$T = 19$	$T = 18$	$T = 17$	$T = 16$	$T = 15$	$T = 14$
Simple Method	$\tau = 99$	$\tau = 99$	$\tau = 99$	$\tau = 99$	$\tau = 99$	$\tau = 99$
Kingman	$\tau = 185$	$\tau = 93$	$\tau = 63$	$\tau = 48$	$\tau = 39$	$\tau = 32$
Diffusion and Beneš	$\tau = 99$	$\tau = 86$	$\tau = 78$	$\tau = 72$	$\tau = 68$	$\tau = 65$

By definition the simple method is insensitive to the T value as long as $T \leq T_{CBR}$. The Kingman method is in contrast highly dependent of the T value, and especially for T close th T_{CBR} it gives very large figures even larger than the first method. The explanation for the divergence of τ by the Kingman bound is that the CDV affected cell stream contains non-neglectable negative correlations and since the Kingman bound is based on a renewal assumptions, it cannot take into accound correlations and it gives a severe overestimation of the τ value for T close to T_{CBR} in both the Poisson and negative binomial cases.

The diffusion method combined with Beneš bound takes into account correlations and as the Kingman bound method τ increases with T but does not posess the same dramatic behaviour when T approaches T_{CBR}. On the other hand the method gives much larger figures than the Kingman for big over-allocations and in the binomial case the figures are even larger than those provided by the simple method. This disappointing behaviour has two causes. First we have applied the Beneš upper bound which overestimates the non-conformance ratio. Second, and this is more important, then the Beneš method gives estimates of the probability of exceeding a given queue length at an arbitrary time. What is needed is the probability at an arbitrary arrival. For higly regular processes like here, this gives rise to a gross overestimation of the non-conformance ratio. It also explains while the the Binomial case is the worst, since it this case gives the most regular CDV perturbated CBR stream.

4.2 Tandem Queues

In this section we illustrate how the application of the simplified heavy load approximation and the light load approximation leads to values for the CDV tolerance when the CDV perturbated CBR connection is approximated by a renewal process and the Kingman bound is used to compute the tolerance value τ.

4.2.1 Heavy Load

Here we present a table in which the variance of the inter-departure time of the CDV perturbated CBR cell stream is computed based on formula (9). From this value the required CDV tolerance is found from the Kingman bound based on a non-conforming ratio of 10^{-9} and an over-allocation factor of 1.11 ($T = 18$). As inter-departure time distribution we have used a Gamma distribution from which the mean and variance can be matched with 100% accuracy.

Table 4: Variance of inter-departure time and needed CDV Tolerance based on Kingman. Load in each tandem queue is 1.

	$M = 1$	$M = 2$	$M = 4$	$M = 8$	$M = 16$	$M = 32$	$M = \infty$
variance of interdep.	19	36.1	65.6	109	157	188	210
required CDV tolerance	$\tau = 86$	$\tau = 162$	$\tau = 295$	$\tau = 491$	$\tau = 709$	$\tau = 845$	$\tau = 946$

As can be seen from the table then the convergence to the limit variance requires more than 30 tandem queues when $T_{CBR} = 20$. When the load is smaller than 1, the convergence becomes even slower, see e.g figure 3 in [9].

4.2.2 Light Load

Here we present the corresponding table when the load from the interfering traffic is light and formula (10) applies. Again the Kingman bound has been applied and the over-allocation factor is $1.11(T = 18)$.

Table 5: Variance of inter-departure time and needed CDV Tolerance based on Kingman. Load in each tandem queue is 0.4.

	$M = 1$	$M = 2$	$M = 4$	$M = 8$	$M = 16$	$M = 32$	$M = 64$
variance of interdep.	0.12	0.25	0.49	0.98	1.96	3.92	7.84
required CDV tolerance	$\tau = 1$	$\tau = 2$	$\tau = 3$	$\tau = 5$	$\tau = 9$	$\tau = 18$	$\tau = 36$

One of the consequences of the light load approximation when the Taylor approximation is carried out to second order only, is that at most two arrivals in a slot can be modelled and what is worse, at most +/- one time slot deviation from the periodic nature is allowed per queue. This approach therefore only works for very light load, and the application to UPC dimensioning with the estimation of very tiny probabilties is questionable. This also explains the very low tolerances displayed for few hops in table 5.

5 Conclusions

In this paper we have presented three different models by which it is possible to find the parameters of the GCRA when a CBR connection has been perturbated due to cell delay variation in the upstream network. The three models have been evaluated in the case where the upstream network can be modelled as a single FIFO queue with interfering traffic. None of the method has an overall acceptable performance. The simple method yields in general too large figures and is best in case of a small over-allocation factor. The renewal/Kingman based method should only be used when the over-allocation factor is at lest 1.1, and the diffusion/Beneš method which explicitly takes into account correlation yields in general too large figures unless the introduced CDV is significant and the over-allocation factor is small. It appears that using the unfinished work at an arbitrary time (which the Beneš result enforces) instead of the correct unfinished work at an arbitrary arrival in most cases is a larger source of error than neglection the correlations.

In the case where the upstream network can be modelled as a tandem of queues, we are faced with a much more difficult problem. However, the heavy load analysis combined with the Kingman method seem to be a reasonable tool for a worst case dimensioning which does not provide too pessimistic figures.

6 Acknowledgements

We would like to thank TeleDanmark and Ellemtel Telecommunication System Laboratories for financial support.

References

[1] ATM Forum, *Traffic Control and Congestion Control*, Draft Baseline Document, 04-93.

[2] S. Blaabjerg, *Estimating the Effect of Cell Delay Variation by an Application of the Heavy Limit Theorem*, COST 242 TD(92) 017.

[3] S. Blaabjerg, *Cell Delay Variation in a FIFO Queue: A Diffusion Approach*, Proc. of IFIP TC6 High Speed Networks, Raleigh, October, 1993.

[4] J.L.v. Berg, J.A.C. Resing, *The Change of Traffic Characteristics in ATM Networks*, COST 242 TD(92)040.

[5] C. Bisdikian, W. Matragi, K. Sohraby, *A Study of the Jitter in ATM Multiplexers*, Proc. of IFIP TC6 High Speed Networks, Raleigh, October, 1993.

[6] P. Brown and A.Simonian, *Perturbation of a Periodic Flow in a Synchronous Server*, PERFORMANCE'87, P.J. Courtois and G. Latouche Ed. Elsevier Science Publishers, 1988.

[7] COST 224, *Performance Evaluation and Design of Multi-Service Networks*, (ed. J. Roberts), Final Report 1991.

[8] COST 242, *Cell Delay Variation in ATM Networks*, (ed. A. Gravey, S. Blaabjerg), Interim Report, 1994.

[9] A. Gravey, L. Romœuf, K. Sevilla, S. Blaabjerg, *Models for Setting ATM Parameter Values*, RACE Traffic Expert Workshop, 1995.

[10] F. Guillemin, P. Boyer, A. Dupuis, L. Romoef, *Peak Rate Enforcement in ATM Networks*, Proc. of IEEE INFOCOM'92, Session 6A, Florence 1992.

[11] F. Guillemin, J. W. Roberts, *Jitter and Bandwidth Enforcement*, Proc. of IEEE GLOBECOM'91, paper no. 9.3, Phoenix, AZ, USA, Dec. 2-5, 1991.

[12] F. Hübner, *Dimensioning of a Peak Cell Rate Monitor Algorithm Using Discrete Time Analysis*, ITC-14, France, Session E31, 1994.

[13] ITU-T SG 13 Recommendation I.356, BISDN ATM *Layer Cell Transfer Performance.*

[14] ITU-T SG 13 Recommendation I.371, *Traffic Control and Congestion Control in B-ISDN.*

[15] J.F.C. Kingman, *Inequalities in the Theory of Queues*, Journal of the Royal Statistical Society, Series B, **32**, pp. 102-110 (1970)

[16] F.P. Kelly, P.B. Key, *Dimensioning Playout Buffers for an ATM Network*, 11th UK Teletraffic Symposium (Cambridge, 1994), IEE Savoy Place, London.

[17] L. Kleinrock, *Queueing Systems* Vol II, Wiley Interscience.

[18] W. Matragi, C. Bisdikian, K. Sohraby, *Jitter Calculus in ATM Networks: Single Node Case*, Proc. of INFOCOM'94, pp. 232-241, June, 1994.

[19] W. Matragi, K. Sohraby, C. Bisdikian, *Jitter Calculus in ATM Networks: Multiple Node Case*, Proc. of INFOCOM'94, pp. 242-251, June, 1994.

[20] G. Niestegge, *The Leaky Bucket Policing Method in the ATM Network*, Int. Journal f Digital and Analogue Communications Systems, Vol 3, 1990.