Buffer and Throughput Analysis of the Explicit Rate congestion Control Mechanism for ABR services in ATM Networks

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Abstract

In this paper we consider ABR traffic which shares an output port of a switch with delay sensitive CBR/VBR traffic. Congestion control of the ABR traffic is achieved by means of an Explicit Rate control scheme. Two important performance measures are evaluated using an analytical model: the ABR-buffer occupancy distribution in the switch and the ABR traffic throughput. We consider two types of ABR traffic sources: persistent (or greedy) sources and on/off sources. Application of the analysis on numerical examples illustrate the influence of the following system characteristics on the performance measures: (i) distance between the ABR source and the switch, (ii) the variability of the CBR/VBR traffic, (iii) the frequency by which the Allowed Cell Rate of the ABR source is updated, (iv) duration of idle period of ABR traffic generation.

keywords ATM, Traffic Management, Congestion Control, Available Bit Rate, Explicit Rate Congestion Control.

1 Introduction

In order to allow for different service types, each with their specific Quality of Service (QoS) requirements, the Asynchronous Transfer Mode (ATM) needs adequate traffic
management mechanisms. For real-time service categories, such as Constant Bit Rate (CBR) and Real-Time Variable Bit Rate (rt-VBR) traffic services, the network applies preventive open loop control mechanisms. Connection Admission Control (CAC), Usage Parameter Control/Network Parameter Control (UPC/NPC) and Traffic Shaping belong to this class of traffic control mechanisms. Open loop control requires an adequate prediction and control of the traffic volume and its profile. This is achieved by means of a traffic contract established between the source and the network at call set-up. For data traffic services, such a prediction is difficult (if not impossible), and therefore open loop schemes are not efficient in this case, as they may result in a considerable waste of network resources. For this class of traffic services, referred to as Available Bit Rate (ABR), a closed loop control scheme seems to be more appropriate since it may use the remaining bandwidth more efficiently. Such a closed loop scheme dynamically regulates the cell rate of a connection based on feedback information from the network.

For the ABR service class, there are strict QoS guarantees towards the Cell Loss Ratio (CLR), but no guarantees towards delay or delay variation. The network and the source may agree upon a Minimum Cell Rate (MCR) and a Peak Cell Rate (PCR). Between MCR and PCR, the network guarantees a low CLR, as long as the Source End Station (SES) adapts its cell rate to the feedback information received from the network.

Since the notification process involves a round trip delay of twice the distance between SES and switch, the network has to provide large buffers in the switches to cope with the low cell loss guarantees in the presence of this notification delay.

The ATM Forum ([1]), has proposed a number of congestion control mechanisms for the ABR service class. The two most important classes of proposals are the credit-based schemes and the rate-based schemes. Eventually the rate-based scheme was adopted as solution for congestion control of the ABR service class. Within the rate-based solution different feedback mechanisms have been proposed, of which the Binary Feedback Congestion Control mechanism and the Explicit Rate Congestion Control scheme are the most important ones. The results in this paper restrict to Explicit Rate schemes. In this class of schemes, switches compute the rate a source should use to emit cells, called Explicit Rate (ER), and this rate is communicated to the source by means of Resource Management (RM) cells. From this ER, the source determines the Allowed Cell Rate (ACR) according to an algorithm specified by the ATM Forum (see [1]). This rate always satisfies the relationship \( MCR \leq ACR \leq PCR \). Several ways of computing the ER have been proposed, e.g. Enhanced Proportional Rate Control Algorithm (EPRCA), Explicit Rate Indication for Congestion Avoidance (ERICA), etc... (see [5], [6]).

In this paper, we consider a simple network configuration to evaluate the required buffer space for ABR traffic and the throughput of ABR traffic. We consider two traffic sources, a CBR/VBR traffic source and an ABR traffic source, both connected to a switch. The CBR/VBR traffic source generates a variable bit rate traffic, modeled by means of a D-BMAP (see [2]), while for the ABR traffic source two cases are considered,
namely a greedy (or persistent) ABR traffic source and an on/off ABR traffic source. Congestion control of the ABR traffic is achieved by means of an Explicit Rate scheme (which is based on the ERICA scheme ([6])), where the Allowed Cell Rate is updated on a periodical basis (every $P$ timeslots). The model takes the distance between ABR-SES and switch ($2\tau$ timeslots) into account. We derive for the case $2\tau \leq P$ the queue length distribution of the ABR queue in the switch and the throughput of the ABR traffic. In numerical examples, we investigate the influence of the following system characteristics on these performance measures: (i) distance between the ABR source and the switch, (ii) the variability of the CBR/VBR traffic, (iii) the frequency by which the Allowed Cell Rate of the ABR source is updated, (iv) duration of idle period of ABR traffic generation.

2 A Queueing Model for the Evaluation of Explicit Rate Congestion Control in ATM Networks

2.1 Configuration

We evaluate the ABR buffer occupation and the ABR traffic throughput of a system consisting of two end stations and a switch (see Figure 1). One end station generates CBR/VBR traffic and the other end station generates ABR traffic according to an explicit rate congestion control scheme. Both the ABR and CBR/VBR traffic are input to the switch and are competing for the bandwidth of the same output port in the switch. The switch acts as a virtual destination station for the ABR traffic. The distance between the ABR-SES and the switch is $\tau$ time slots, where a time slot is the time needed to process a cell in the switch (and chosen as time unit). The various components and their behavior is now described in more detail.

![Figure 1: The Configuration of the Model](image)
2.2 Source Behavior

We consider two end stations, namely a CBR/VBR traffic end station, referred to as CBR/VBR-SES, and an ABR traffic traffic end station, referred to as ABR-SES. Let us describe the two sources in detail.

a. CBR/VBR Traffic Model

In [2], the class of discrete-time Batch Markovian Arrival Processes (D-BMAP) has been proposed as generic traffic model for VBR traffic in ATM networks. In particular, the superposition of on/off processes, a model for VBR video traffic, belongs to this class. This superposition has two types of rate changes, each occurring at a different time scale: at burst time scale, the rate changes according to the number of on/off sources which are in the on state (i.e. low frequent changes) and at cell time scale, the rate changes according to the number of cells arriving in a slot for a fixed number of sources in the on state. We briefly recall the definition of the D-BMAP model. For more details we refer the reader to [2].

Consider $M$ discrete-time on/off sources, with geometrically distributed on period (mean on period $p$ time slots), geometrically distributed off period (mean off period $q$ time slots) and a probability of $\lambda/d$ to generate a cell in a slot during the on period. The superposition of these on/off sources can be described by the following process. Consider the discrete-time Markov chain with transition matrix $D$ describing the number of sources which are in the on state. Suppose that at time $k$ there are $i$ sources in the on state, $1 \leq i \leq m$. At the next time instant $k + 1$, there occurs a transition to another or possible the same number of sources in the on state and a batch arrival may or may not occur. With probability $(d_0)_{i,j} = 1 \leq i \leq m$, there is a transition to state $j$ without an arrival, and with probability $(d_n)_{i,j} = 1 \leq i \leq m, n \geq 1$, there is a transition to state $j$ with a batch arrival with size $n$. When $i$ sources are in the on state, then the probability that $n$ cells are generated during a cell slot is given by

$$c_n(i) = \binom{i}{n} \left( \frac{1}{d} \right)^n \left( \frac{d-1}{d} \right)^{i-n}.$$  

Clearly the matrix $D_0$ with elements $(d_0)_{i,j}$ governs transitions that correspond to no arrivals, while the matrices $D_n$ with elements $(d_n)_{i,j}, 1 \leq i \leq m, n \geq 1$, govern transitions that correspond to arrivals of batches of size $n$.

In the sequel we need the following notations. Define the matrices $A_j^{(n)}$ as follows

$$D^n(z) = \sum_{i=0}^{m} D_i z^i = \sum_{j=0}^{n} A_j^{(n)} z^j, \quad n \geq 1.$$  

b. ABR Traffic Model

We consider two cases: case A where the ABR source is a persistent (or greedy) source, i.e. this source has always cells to transmit and will do so at maximal allowed cell rate, and case B where the ABR source is an on/off source. This on/off traffic has the same characteristics as described above in (a) and is also characterized by
three parameters: the mean on period, the mean off period and the cell rate while in an on period. The rate at which cells can be transmitted is called the Allowed Cell Rate (ACR). The ACR varies between the Peak Cell Rate (PCR) and the Minimum Cell Rate (MCR), both values being defined at call setup. Moreover, the ABR-SES initially starts transmitting at a rate ICR (Initial Cell Rate). Every \( P \) time slots, the ABR-SES receives a notification of the new ACR to be used during the next \( P \) time slots from the switch by means of the value in the ER field in a backward RM cell. The interval \( P \) is called an observation period. It determines the time scale according to which the ACR adopts to the state of the network. We simplify the behavior of the SES as we let the ACR be completely determined by the ER, not taking into account additive increase and multiplicative decrease factors (see [1]). In case A, the ABR-SES generates traffic according to the allowed rate ACR, while in case B, the actual rate that is used depends on both the allowed rate ACR and the state of the ABR source. In what follows we need the following notation. As an on/off source is a special case of a D-BMAP, we let, similar to the CBR/VBR traffic model, \( C_1 \), resp. \( C_0 \), be the \( 2 \times 2 \) matrices describing the on-off transition with, resp. without, arrivals. Let 

\[
C(z) = C_0 + zC_1
\]

and denote

\[
C^n(z) = (C_0 + zC_1)^n = \sum_{j=0}^{n} B_j(z)z^j.
\]

Remark 1. For reasons of tractability we assume that in case B, when ABR cells are generated during an on period at a rate higher than the ACR (i.e. not all cells can be sent immediately due to a low ACR), then the cells that cannot be transmitted are NOT stored in an SES buffer. This assumption is motivated by the following observations:

- The evaluation is focusing on the ABR buffer occupancy in the switch, and not on a buffer in the ABR-SES.
- The aim of considering case B is to investigate the influence of the presence and the duration of a silent period for ABR traffic (see numerical examples).

2.3 Switch Behavior

During an observation period \( P \), the switch counts the number of arrivals from both the CBR/VBR traffic source and from the ABR traffic source. Denote these numbers by \( N_C \), resp. \( N_A \). The total input rate of the switch during this observation period is then 

\[
i = (N_C + N_A)/P \text{ cells per slot}
\]

Let the desired utilization of the output link of the switch be TCR (Target Cell Rate). Then the overload factor is given by 

\[
o = i/TCR.
\]

The explicit rate communicated to the SES is given by

\[
r = \min \{PCR \cdot \max [MCR, \frac{CCR}{o}] \}.
\]

The variable CCR refers to the Current Cell Rate field of the RM cell and has to be set to the current ACR by the source according to the ATM Forum specifications. When the ABR source is silent during a certain period, the ABR-SES has to drop the ACR
In this paper, we let the CCR be the rate actually used by the ABRSES, i.e. \( CCR = \frac{N_o}{P} \). In case A of a persistent ABR source, this rate is exactly the ACR.

From the above computation of the ACR it follows that the ABR-SES is always guaranteed a minimum cell rate MCR. Although we do not discuss the scheduling mechanism to be used in the switch, this implies that at the output port, the ABR traffic should be guaranteed a service rate of at least MCR.

**Remark 2.** In order to not unnecessarily complicate the model, CBR/VBR cells which are not served during an observation period \( P \) are not stored in the switch. This assumption is motivated by the following observations:

- The aim of having CBR/VBR traffic in the model is to let the capacity available for ABR traffic vary in time. The evaluation is focused on ABR traffic performance, not on CBR/VBR traffic.
- CBR/VBR traffic is buffered only when simultaneous cell arrivals occur. The buffers are not used to store bursts, and hence they are rather small.

### 2.4 Performance Measures

The performance measures we are interested in are the occupation of the ABR buffer in the switch and the throughput of the ABR traffic. In particular we are interested in the \( 10^{-9} \) quantile of the queue length distribution and the mean throughput of the ABR traffic. The evaluation of these measures is given in the next Section.
3 Analysis of the Queueing Model

3.1 Evolution of the process

Figure 2 illustrates the interaction between the ABR-SES and the switch. We observe that during an observation period of length $P$, two rates for the ABR traffic apply. Indeed, consider the interval $[nP, (n + 1)P]$.

- The observation made by the switch during the interval $[(n - 2)P, (n - 1)P]$ will determine the ACR used by the ABR-SES in the interval $[(n-1)P+2\tau, nP+2\tau]$, and in particular during the interval $[nP, nP + 2\tau]$ (as $2\tau \leq P$). We denote this rate by $r_{old}(n)$.

- The observation made by the switch during the interval $[(n - 1)P, nP]$ will determine the ACR used by the ABR-SES in the interval $[nP + 2\tau, (n + 1)P + 2\tau]$, and in particular during the interval $[nP + 2\tau, (n + 1)P]$. We denote this rate by $r_{new}(n)$.

Let us describe the system at the end of each observation period, i.e. at instances $nP$, $n = 1, 2, 3, \ldots$, by means of the following vector

$$\mathbf{S}(p_c(n), p_a(n), r_{old}(n), r_{new}(n)) = \mathbf{S}(n),$$

whereby

- $p_c(n)$ is the phase of the CBR/VBR traffic at instant $nP$;
- $p_a(n)$ is the state of the ABR traffic source at instant $nP - \tau$;
- $r_{old}(n)$ is the ACR computed by the switch at the end of the observation period $[(n - 2)P, (n - 1)P]$, i.e. the ACR applied by the ABR-SES during the interval $[(n - 1)P + 2\tau, nP + 2\tau]$;
- $r_{new}(n)$ is the ACR computed by the switch at the end of the observation period $[(n - 1)P, nP]$, i.e. the ACR applied by the ABR-SES during the interval $[nP + 2\tau, (n + 1)P + 2\tau]$.

Let us now show how the transition $\mathbf{S}(n) \rightarrow \mathbf{S}(n + 1)$ can be computed. Let $\mathbf{S}(n) = (i_0, j_0, \mu_0, \nu_0)$.

(i) First we compute the joint distribution of the number of CBR/VBR arrivals and the phase of this process. Denote $N_c[t_0, t_1]$ the number of CBR/VBR arrivals during the interval $[t_0, t_1]$. Then clearly

$$\mathbf{P}\{p_c(n + 1) = i_1, N_c[nP, (n + 1)P] = l | p_c(n) = i_0\} = [\mathbf{A}_i^{(P)}]_{i_0, i_1},$$

where $[\mathbf{X}]_{i,j}$ denotes the $(i,j)$-th element of the matrix $\mathbf{X}$ and where $\mathbf{A}_i^{(P)}$ is defined in Section 2.2.

(ii) (this step is only necessary in case B) We compute the joint distribution of the number of ABR arrivals and the state of the ABR source during an interval of length $P$. Using the notations introduced in Section 2.2

$$\mathbf{P}\{p_a(n + 1) = j_1, N_a[nP, (n + 1)P] = k | p_a(n) = j_0\} =$$
where the first sum is taken over all possible \((k_1, k_2)\) such that
\[
k = \min \left[ \left\lfloor 2\tau \mu_0 \right\rfloor, k_1 \right] + \min \left[ \left\lfloor (P - 2\tau)\mu_0 \right\rfloor, k_2 \right].
\]

In this formula \([x]\) denotes the largest integer smaller or equal than \(x\).

(iii) Clearly \(r_{\text{old}}(n + 1) = r_{\text{new}}(n)\).

(iv) Now we compute \(r_{\text{new}}(n + 1)\). We need to compute the number of ABR arrivals during \([nP, (n + 1)P]\). First we consider case A. As two ACR’s apply, we compute the two corresponding components separately. During \([nP, nP + 2\tau]\) the rate \(r_{\text{old}}(n) = \mu_0\) applies, hence the number of ABR arrivals during that period equals \(2\tau \mu_0\). Similarly, the number of ABR arrivals during the interval \([nP + 2\tau, (n + 1)P]\) is given by \((P - 2\tau)\mu_0\). Hence, the total number of ABR arrivals is
\[
N_a[nP, (n + 1)P] = \left[2\tau \mu_0 + (P - 2\tau)\mu_0\right]P
\]

In case B, the number of ABR arrivals is given by the computation in (ii). If there are \(N_anP, (n + 1)P\) of CBR/VBR arrivals (see (i)), then the new ACR is given by
\[
r_{\text{new}}(n + 1) = \min \left[PCR \max \left[MCR \frac{r_{\text{new}}(n)}{N_{\text{tot}}}, TCR\right], \right]
\]

with \(N_{\text{tot}} = N_a[nP, (n + 1)P] + N_a[nP, (n + 1)P]\).

### 3.2 Buffer Analysis

From the above analysis, we know the rates at which ABR cells arrive at the ABR queue in the switch during an interval \([nP, (n + 1)P]\). Let this number be denoted by \(N_a\). The CBR/VBR traffic has priority, i.e. is served first, but such that ABR traffic has a guaranteed service rate of MCR, i.e. of every \(P\) slots there are \(MCR \times P\) slots reserved for ABR cells (if there are ABR cells available that can use these slots). Hence, if \(N_c\) cells of CBR/VBR traffic arrive during \([nP, (n + 1)P]\), and taking into account Remark 1, the number of slots available for serving ABR cells, is given by
\[
B = \max \left[ MCR \times P - N_c \right].
\]

Denote by \(Q(n)\) the queue length of the ABR buffer in the switch at instant \(nP\). Then we can describe approximately the evolution of the queue length as follows:
\[
Q(n + 1) = \max \left[0, Q(n) + N_a - B\right].
\]

The process \(Q(n)\) forms a Markov chain with the following transition matrix. Let \(C_i\) the matrix describing the transition of the variables \((p_c, p_{old}, r_{\text{old}}, r_{\text{new}})\) giving rise to a growth \(i\) in number of ABR cells during an observation period \(P\). Clearly
\[
-P \leq i \leq \left|PCR \times P\right| \leq P.
\]
For simplicity reasons we let $-P \leq i \leq P$. The transition matrix is given by

$$
P = \\
\begin{pmatrix}
\sum_{i=-P}^{0} C_i & C_i & \ldots & C_P & 0 & 0 & 0 & \ldots \\
\sum_{i=-P}^{0} C_i & C_0 & \ldots & C_{P-1} & C_P & 0 & 0 & \ldots \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
C_{-P} & C_{-P+1} & \ldots & C_0 & C_1 & \ldots & C_{P-1} & C_P \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \ddots & \vdots \\
\end{pmatrix}
$$

Remark that $P$ is finite, but for simplicity reasons the boundary matrices are omitted.

By grouping the matrices $C_i$ in the appropriate way, we obtain the following Quasi Birth-Death (QBD) process:

$$
P = \begin{pmatrix}
A_0 & U \\
D & A & U \\
& \ddots & \ddots & \ddots & \ddots \\
& D & A & U \\
& & D & A & \ddots \\
\end{pmatrix}
$$

with

$$
D = \begin{pmatrix}
C_{-P} & C_{-P-1} & \ldots & C_{-1} \\
0 & C_{-P} & \ldots & C_{-2} \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & C_{-P} \\
\end{pmatrix}, \quad \Gamma = \begin{pmatrix}
C_P & 0 & \ldots & 0 \\
C_{P-1} & C_P & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
C_1 & C_2 & \ldots & C_P \\
\end{pmatrix}
$$

Now it is possible to apply a classical algorithm to compute the steady state vector of a QBD process, e.g. the folding algorithm ([9]) or the algorithm explained in [2].
3.3 Throughput Analysis

The throughput $t(n)$ of the ABR traffic in the switch during the interval $[nP, (n + 1)P]$ is given by

$$ t(n) = \min \left[ 1, \frac{N_a}{B} \right] \times B, \quad (3) $$

where $N_a$ is the total number of ABR arrivals during $[nP, (n + 1)P]$, and $B$ is the number of slots available for serving ABR cells during that interval, given by (2). Now we can form a Markov chain with state space $\mathcal{S}(n) = (\mathcal{S}(n), t(n))$, the transition matrix of which can be computed using the results of Section 3.1. and (3). The steady state of this Markov chain leads to the distribution of the throughput of the ABR traffic in the switch. The mean value of this distribution is called the throughput of the ABR traffic, denoted by $\bar{T}$.

4 Numerical Examples

4.1 Example 1: Influence of the Burstiness of CBR/VBR traffic

In this first example, we investigate the influence of the burstiness of the CBR/VBR traffic on the performance of the ABR traffic, in particular on the ABR queue length and the ABR traffic throughput. The CBR/VBR traffic is modeled as a superposition of 3 on/off sources, and we vary the burstiness by varying the length of the ON period, letting the bit rate while in an ON state of each source constant and keeping the arrival rate of each source unchanged. The parameters that are used are given as follows:

For the system: $\tau = 3, T = 6$.
For the ABR traffic: TCR = 0.5, PCR = 0.9; MCR = 0.3.
For the CBR/VBR traffic: number of on/off sources $m = 3$, probability of generating a cell while ON is $1/d = 1/4$, leading to an arrival rate of each source of $1/12$, the mean ON period is variable ($p = 10, 50, 100, 150, 200$) and the mean off period is $q = 2 \times p$.

Figure 3 shows the buffer capacity needed to guarantee a cell loss smaller than $10^{-9}$, while Figure 4 shows the mean throughput $\bar{T}$ for the ABR traffic, both for variable ON period of the individual on/off sources.

5 Conclusions

In this paper we have given an analytical evaluation of the buffer occupancy and throughput of ABR traffic when sharing a link with CBR/VBR traffic and using an Explicit Rate congestion control scheme. Numerical examples show that the burstiness of the CBR/VBR traffic has an important influence on the ABR performance.
Figure 3: Required buffer capacity to guarantee CLR < 10^{-9}

Figure 4: Mean Throughput of ABR traffic

References


