# A General Traffic Control Framework in ATM Networks

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**Abstract**

This paper presents a novel *traffic control framework* for Asynchronous Transfer Mode (ATM) based networks which incorporates the control of Constant Bit Rate (CBR), real time Variable Bit Rate (rtVBR), non-real time Variable Bit Rate (nrtVBR), Available Bit Rate (ABR) and Unspecified Bit Rate (UBR) Virtual Channel Connections (VCC's). The control is based on the *complete buffer partitioning* architecture and on the associated buffer scheduling rule with adaptive *weighting functions*. We define a 3-dimensional *Quality of Service (QoS) state space* where the axes are the cell loss probability (CLP), cell delay (CD) and cell delay variation (CDV) parameters assigned to each VCC. We formulate the traffic control task as an optimization problem, where the sum of the abstract distances of the QoS points is to be minimized subject to the constraint that all negotiated QoS parameters must fall into the negotiated QoS region. We suggest a *dynamic programming* (DP) approach to the solution. With a simulation case study the flexibilty and appropriateness of the framework are shown.

## 1 Introduction

As ATM networks are to support CBR, rtVBR, nrtVBR, ABR and UBR service classes, simple 2-level priority based control policies become inadequate [11, 3]. Furtheremore, within these service classes different VC connections may require different cell loss, cell delay and cell delay variation parameters. It is therefore essential that the traffic control strategies be capable for the provision of the negotiated QoS parameters and for high network utilization by statistically multiplexing traffic classes with strict (CBR and VBR) or with limited (ABR) QoS guarantees with a pure best effort type service class (UBR). Indeed, one of the key issues in the success of ATM is the traffic integration, and specifically, the design and analysis of control strategies which make this integration possible. The need for a fine granularity of traffic control in ATM has been recognized e.g. in [11] and [3] where a 4-level priority based control mechanism is proposed. This model classifies traffic classes as "sensitive" or "less sensitive" to loss and delay. Gelenbe et al. concentrates on minimizing the impact of cell loss where cells belonging to different classes are assigned a cost function representing the importance of cells belonging to different "sessions", i.e. VCC's, [4]. It is envisaged, that second generation ATM switches will employ the Generalized Processor Sharing (GPS) and its packetized version, PGPS, as the basic principle for buffer management, [8, 10]. In the more theoretical vein, recently there has been a growing interest in devising stochastic control methods, which can serve as a theoretical basis in the engineering of control enabling traffic integration in ATM, see e.g. [5] and [9].

The purpose of this paper is to present a traffic control framework which allows for arbitrary degree of granularity in terms of guaranteed QoS parameters in an ATM network where service classes with and without QoS guarantee, with and without congestion control, and with and without real time guarantees are present. It follows from this objective that the control cannot be based on a single bit, like the Cell Loss Probability (CLP) bit found in the ATM header. This is not only because a single bit cannot contain enough information on a complex QoS measure, but also because the continouos ("real time") QoS monitoring of VCC's is both required and feasible by current and next generation ATM switches. We propose a scheme where the control is based on the (1) negotiated QoS parameters, (2) instantenouos (current) QoS of the VCC under control, and (3) network resources allocated for the VCC under control. This is achieved by (1) defining a 3-dimensional QoS state space where the QoS parameters of each VCC can exactly (or with arbitrary prcision) be desrcibed and (2) by a complete buffer partitioning with complete link capacity sharing [6] architecture of ATM multiplexers, which allows for "an individual handling" of VCC's requesting sharply different QoS measures from the network. It follows that a buffer partition arbitration algorithm is needed, which decides (possibly at each time slot) which partititon's cell(s) gets served next. The basic requirements to this algorithm are that (1) it should guarantee the negotiated QoS parameters to each VCC and (2) it should optimize the "overall" network performance in the sense that provided that (1) is kept, each VCC gets the highest possible quality of service while network utilization is aslo kept high. Since the algorithm is to be executed real time, it should be simple and feasible by current technologies.

## 2 The Traffic Control Framework

The general purpose of traffic control is to protect the network and the user in order to achieve network performance objectives with optimum allocation of network resources [14]. To fulfill these objectives QoS, traffic and network information are required for the generic traffic control functions. We have chosen the following parameters for our traffic control framework which is in agreement with the standardization work of ATM Forum [15, 16] and ITU-T [13, 14]:

- **Connection Traffic Descriptors**: Peak Cell Rate (PCR), Cell Delay Variation Tolerance (CDVT), Sustainable Cell Rate (SCR), Maximum Burst Size (MBS), Minimum Cell Rate (MCR) and the conformance definition: the Generic Cell Rate Algorithm (GCRA) [14]
- **Quality of Service Parameters**: Cell Loss Ratio (CLR), average Cell Transfer Delay (CTD), peak-to-peak Cell Delay Variation (CDV)
- **Network Resources**: link capacities (C), memory size for buffering (Q)

The proposed traffic control method based on the *complete buffer partitioning* architecture (Fig. 1) where the total switch memory is devided to five FIFO buffers according to the presently considered service categories: CBR, rtVBR, nrtVBR, UBR and ABR [16]. For the ABR class the end-to-end rate based (or credit based) mechanism can also be present. The Connection Traffic Descriptors should be

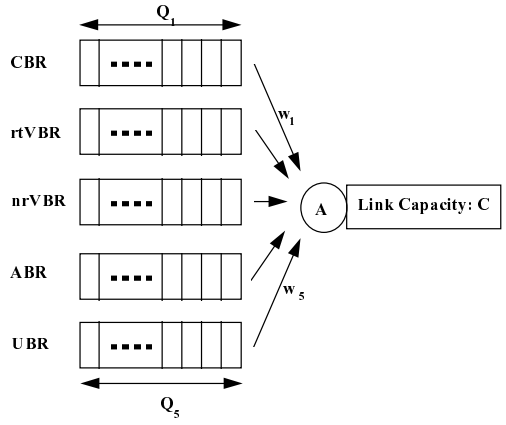


Fig. 1: The Complete Buffer Partitioning Architecture

selected in corporation with the proper dimensioning of Usage Parameter Control (UPC) [16, 1]. An efficient Call Admission Control (CAC) can be performed with buffer partitioning and bandwidth allocation based on the listed parameters. We use as starting point the results of the CAC so we get the buffer sizes ($Q_i$) as input parameters to our traffic control method.

The motivation behind choosing the complete buffer partitiong scheme is that previous works clearly demonstrated that at the pesence of all these inherently different services having also rather diverse QoS requirements the complete buffer partitioning based schemes are superior over shared buffering techniques [11, 3, 6]. In our model a *weighting function ($w_i$)* is dedicated to each buffer. The cell scheduling rule is the following: all weighting functions are evaluated at each time slot and the Head of Line (HOL) cell of the buffer with the greatest weighting funtion value is forwarded to the output link. The appropriate choice of the weighting functions is a crucial point of the control. The weigthing function uses the Connection Traffic Desriptors, QoS Parameters, Network Resource settings and also the instantenous (current) QoS information of the VCC under control. The idea of weighting functions allows us to set a flexible traffic control method. An application example of setting the weighting functions can be found in Section 4.

We define a 3-dimensional state space with coordinates of measures of cell loss, delay and delay variation characteristics. We chose for these measures the instantenous CLR, CTD, and CDV parameters of a connection. In this state space the QoS evolution of VCs can be observed where acceptence regions can also be identified based on the negotiated QoS parameters. We define a *cost function* as an abstract distance of the actual QoS from the origin in the state space. The tasks of the traffic control method is thereafter formulated as to find the appropriate weighting functions such that:

- the actual QoS values for each VC should be whithin the negotiated region
- the total cost of all VC connections should be minimal

These objectives with the related optimization problem are mathematically formulated in Section 3.

For the five service categories different traffic parameters and QoS parameters should be specified. Our assignment (Table 1) is mainly based on the ATM Forum specifications [16]. The weighting functions should reflect the parameters specified by Table 1 (see Section 4 for an application example). The end-to-end performance objectives of negotiated QoS Parameters should be allocated among the connection portions. We use the allocation principles specified in the standardization works, i.e. the CTD and CLR objectives are allocated by additive rules and the CDV objectives are determined by the square root rule [13, 17]. Having the performance objectives for each switch after this decompozition, our control method can be performed locally in the switches. Note that using the local performance objectives,

| Attribute | CBR | rt-VBR | nrt-VBR | UBR | ABR |
|---|---|---|---|---|---|
| Traffic Parameters | | | | | |
| PCR, CDVT | X | X | X | X | X |
| SCR, MBS, CDVT | | X | X | | |
| MCR | | | | | X |
| QOS Parameters | | | | | |
| CDV | X | X | | | |
| CTD | X | X | | | |
| CLR | X | X | X | | X |

Table 1: Traffic and QoS Parameters

local resource settings and the instantenous local QoS information with the given Connection Traffic Descriptors the general end-to-end traffic control problem is decomposed to *local traffic control problem* in each switch. Also note that this control can coexist with the end-to-end ABR control mechanism.

## 3 The Optimization Task

### 3.1 System Equations

Consider the buffer partititon in Fig. 2. The lower index $i$ refers to the service class ($i = 1..5$, i=1: CBR, i=2: rtVBR, i=3: nrtVBR, i=4: ABR, i=5: UBR), the upper index $(k)$ refers to the $k$th time slot. The state of the system at each time slot is specified by the following variables assigned to the $i$th queue at time $(k)$: $n_i^{(k)}$: the number of processed cells; $l_i^{(k)}$: the number of discarded cells; $q_i^{(k)}$: the length of the queue (i.e. the number of cells in the queue); $\tau_i^{(k)}$: time stamp of the current HOL cell. This stamp is assigned to this HOL cell when entering the buffer. The aggregation of these quantities gives the system state column vector $(X_i^{(k)})^T = (n_i^{(k)}, l_i^{(k)}, q_i^{(k)}, \tau_i^{(k)})$. $Q_i$ is the buffersize of the $i$th partition, $a_i^{(k)}$ is the number of arriving cells and $u_i^{(k)}$ is the number of served cells during the $k$th time slot. In this paper, for simplicity, we do not allow batch arrivals or batch departures, i.e. the latter two quantities are either 0 or 1. Note the $a$ will correspond to the random disturbance while $u$ to the control in the DP algorithm. Also note that all these variables are quantities which can be stored locally at the switch, which ease the formulation of a local control law. With the above notation and assuming $l_i^{(0)} = 0$

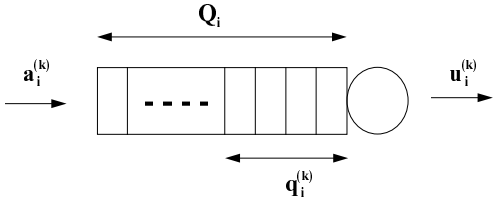


Fig. 2: Notations of Cell Buffering

the system dynamics is described by the following discrete time system equations:

$$q_i^{(k+1)} = min(q_i^{(k)} - u_i^{(k)} + a_i^{(k)}, Q_i) \quad (1)$$

$$l_i^{(k+1)} = max(q_i^{(k)} - u_i^{(k)} + a_i^{(k)} - Q_i, 0) + l_i^{(k)} \quad (2)$$

$$n_i^{(k+1)} = n_i^{(k)} + a_i^{(k)} \quad (3)$$

Note that an alternative to (3) could be:

$$n_i^{(k+1)} = n_i^{(k)} + u_i^{(k)}, \quad (4)$$

but we will assume that $n_i^{(k+1)}$ is large enough to make this difference irrelevant. Obviously, we have the following control constraint: $\sum_i u_i^{(k)} \leq 1$ for all $k$, indicating that at most one queue can get served at any one time.

### 3.2 Instantenous QoS Characteristics

We proceed with relating cell loss probability $c_{i1}^{(k)}$, average (instantenouos) cell delay $c_{i2}^{(k)}$ and average (instantenouos) cell delay variation $c_{i3}^{(k)}$ to the system variables. These definitions are important, because they map the system description to the abstract model of the QoS state space ($i = 1..5$).

$$c_{i1}^{(k+1)} = \frac{l_i^{(k)}}{n_i^{(k)}} \quad (5)$$

$$c_{i2}^{(k+1)} = \begin{cases} \frac{n_i^{(k)} * c_{i2}^{(k)} + (k - \tau_i^{(k)})}{n_i^{(k)}} & \text{if } u_i^{(k)} = 0 \\ c_{i2}^{(k)} & \text{if } u_i^{(k)} = 1 \text{ OR } q_i^{(k)} = 0 \end{cases} \quad (6)$$

$$c_{i3}^{(k+1)} = \begin{cases} \frac{n_i^{(k)} * c_{i3}^{(k)} + (k - \tau_i^{(k)} - c_{i2}^{(k)})}{N_i^{(k)}} & \text{if } u_i^{(k)} = 1 \\ c_{i3}^{(k+1)} & \text{if } u_i^{(k)} = 0 \end{cases} \quad (7)$$

### 3.3 Cost Functional

In this subsection we define the cost functional applicable for optimization with dynamic programming, since it facilitates a straightforward formulation of the Bellman equation [2]. Throughout we restrict our attention to the case when a single traffic source generates traffic to each queue, i.e. each traffic class is represented by a single source (one VCC per queue). This assumption is not especially restricting, since with proper aggregated traffic models the multiple source per service class case can readily be represented. To obtain an overall scaler valued cost functional suitable for optimization, we first need the cost function of a single session, i.e. the cost assigned to a VCC:

$$J_i^{(k)}(c_i^{(k)}) = J_i^{(k)}(c_{i1}^{(k)}, c_{i2}^{(k)}, c_{i3}^{(k)}) = ||J_i^{(k)}|| = \sqrt{{f_{i1}^{(k)}}^2(c_{i1}^{(k)}) + {f_{i2}^{(k)}}^2(c_{i2}^{(k)}) + {f_{i3}^{(k)}}^2(c_{i3}^{(k)})}$$

where the $f_{i1}^{(k)}(.)$, $f_{i2}^{(k)}(.)$, $f_{i3}^{(k)}(.)$ functions are the loss, delay and delay-variation weighting functions, respectively, of $VCC_i$, and $c_i^{(k)}$ is a column vector, corresponding to the QoS of $VCC_i$ at time $k$, $(c_i^{(k)}) = (c_{i1}^{(k)}, c_{i2}^{(k)}, c_{i3}^{(k)})$. Assuming stationarity and equal VCC (session) weighting functions for all $i$, we can neglect the dependency of the weight functions from the $i_1, i_2$ and $i_3$ parameters, as well as from the time index $(k)$. In other words, we simply have:

$$J_i(c_i^{(k)}) = \sqrt{{f_1}^2(c_{i1}^{(k)}) + {f_2}^2(c_{i2}^{(k)}) + {f_{i3}}^2(c_{i3}^{(k)})} \quad (8)$$

Let $\Gamma$ denote the overall cost functional vector, and $C$ denote the cost matrix:

$$\Gamma(C^{(k)}) = (J_i(c_i^{(k)})); C^{(k)} = (c_i^{(k)}); c_i^{(k)} = (c_1^{(k)}, c_2^{(k)}, c_3^{(k)})$$

With this notation the overall scaler cost functional to be minimized takes the form:

$$\gamma(C^{(k)}) = \sum_{i=1}^{5} J_i(c_i^{(k)}) \text{ subject to } C^{(k)} \leq (QoS)_{i,j} \qquad (9)$$

where $i = 1..5, j = 1..3$, and the $QoS$ matrix contains the negotiated QoS parameters (CLR, CTD, CDV), see subsection 4.2. With the above formulation of the optimization problem we are facing the challange of a DP task, where we wish to find the optimal (and feasible) control law $\mu$ which only depends on the state of the physically observable state vector $X$, such that the cost functional is optimized over the 3 dimensional QoS state space represented by the $C$ matrix.

## 4 An Application Example

### 4.1 The Traffic Source Models

In the example below we consider a link of capacity 45 Mbps, and a multiplexer with 5 input channels corresponding to the 5 service classes. The CBR source is of 1.5 Mbps representing DS-1 circuit emulation. The rtVBR, nrtVBR and UBR sources are all modelled as Interrupted Bernoulli Processes (IBPs) and are characterized by their peak and sustainable cell rates, which we set to 15.0-3.0, 22.5-0.5 and 45.0-5.0 Mbps, respectively, representing these typical bursty sources. The ABR source is assumed to be of rate based and is also modelled by an IBP. It is characterized by its peak (22.5 Mbps) and minimum (4.5 Mbps) cell rate. Note that with the above link capacity a time slot in our discrete time model corresponds to 9.422 $\mu s$, which will be used as the time unit in the CTD and CDV values below.

### 4.2 The Weighting Functions

The optimization task as formulated above can be solved by the classical DP approach, if we assume the form of the weighting functions to be known with unknown parameters, which can be obtained as the output of the DP algorithm. Thus, in this section we will assume the following weighting functions obtained by heuristics based on Table 1:

$$w_1 = x_1 * \frac{l_1}{n_1 * CLR_1} + y_1 * \frac{k - \tau_1}{CTD_1} + z_1 * max(k - \tau_1 - CTD_1 - \frac{CDV_1}{6}, 0) \qquad (10)$$

$$w_2 = x_2 * \frac{l_2}{n_2 * CLR_2} + y_2 * \frac{k - \tau_2}{CTD_2} + z_2 * max(k - \tau_2 - CTD_2 - \frac{CDV_2}{6}, 0) \qquad (11)$$

$$w_3 = x_3 * \frac{l_3}{n_3 * CLR_3} \qquad (12)$$

$$w_4 = x_4 * \frac{l_4}{n_4 * CLR_4} \qquad (13)$$

$$w_5 = \begin{cases} x_5 & \text{if } K_1, K_2, K_3, K_4 \text{ are all} > 1 \\ 0 & \text{otherwise} \end{cases} \qquad (14)$$

where:

$$K_1 = \frac{d_1 * (x_1 + y_1 + z_1)}{w_1}; K_2 = \frac{d_2 * (x_2 + y_2 + z_2)}{w_2};$$

and

$$K_3 = \frac{d_3 * x_3}{w_3}; K_4 = \frac{d_4 * x_4}{w_4}$$

These weighting functions reflect the different service classes sensitivity to loss, delay and delay variations and also take into account the required QoS parameters. Specifically, the weighting parameters $x_i$, $y_i$, $z_i$ and $d_i$ are to determine the relative "importance" of a given QoS parameter (out of the 3 considered here) in the weight of a given service class, while the constants $CLR_i$, $CTD_i$ and $CDV_i$ are the negotiated (contracted) cell loss ratio, cell transfer delay and cell delay variation of the respective VCC's. These latter 3 parameters are referred to as $QoS$ in equation (9). With this assumption in hand the DP algorithm now becomes executable, where the outcome of the DP is the $x_i$, $y_i$, $z_i$ and $d_i$ constants.

### 4.3 Numerical Results

Fig. 3-5 display simulation results on CLR, CTD and CDV respectively, when we increase the CBR load from 1.5 Mbps up to 7.5 Mbps. Observe that the load increase affects the UBR CLR only, as desired, since all other classes CLR values are strictly prescribed. The same goes for the CBR and rtVBR classes CTD and CDV parameters. The ABR class is congestion controlled and sensitive to CLR only so its CTD and CDV behaviour is determined by the other classes. In this example we consider a single multiplexer with the weighting functions, where we set $CLR_1 = 10^{-5}$, $CTD_1 = 3.0$, $CDV_1 = 1.0$, $CLR_2 = 10^{-6}$, $CTD_2 = 5.0$, $CDV_2 = 2.0$, $CLR_3 = 10^{-7}$, and $CLR_4 = 10^{-7}$. Note that no delay or jitter parameters are negotiated for the nrtVBR or the ABR service classes. As for the weighting parameters, we use the following settings: $x_1 = 0.1$, $y_1 = 0.6$, $z_1 = 0.9$, $x_2 = 0.2$, $y_2 = 0.3$, $z_2 = 0.4$, $x_3 = 0.6$, $x_4 = 0.4$. As for the UBR service class, we set $x_5 = 6.0$, $d_1 = 0.5$, $d_2 = 0.5$, $d_3 = 0.7$ and $d_4 = 0.6$. These figures show that all QoS characteristics for each class fall within the negotiated QoS region and that the remaining resources are efficiently utilized by the best effort type service classes. This utilization is achieved by keeping the prescribed QoS characteristics close to the negotiated parameters rather than overfulfiling them. The example also demonstrates the statistical multiplexing of five different service classes sharing only 45 Mbps capacity instead of 106.5 Mbps which would be the case of peak rate allocation.

## 5 Conclusions

In this paper we have studied a traffic control framework, the sailient features of which include flexibility in terms of the service classes and QoS parameters it can handle, simplicity in that it rests on information available at the switches and on information processing which requires only

summation and multiplication, and efficiency in that it schedules cells according to the exact QoS values of the different service classes. We have considered a numerical example with the 5 service classes currently standardized by the ATM Forum. In the demonstrated example all QoS requirements have been met with effiecient bandwith utilization. We conclude that the complete buffer partitioning with complete link capacity sharing with adaptive weighting functions architecture is capable to keep the traffic contracts for the classes with strict QoS requirements and distribute resources to best effort type classes as such resources become available.

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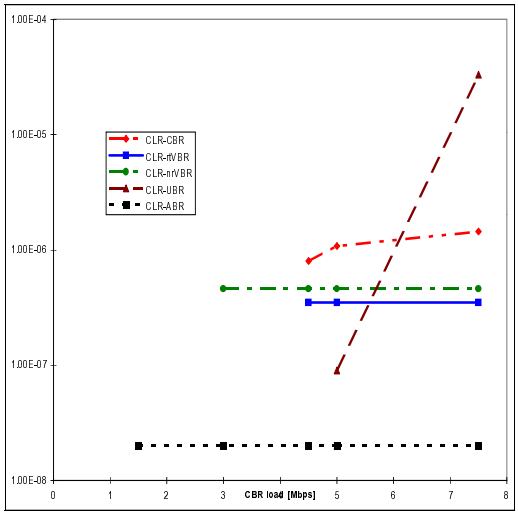


Fig. 3: Cell Loss Ratio

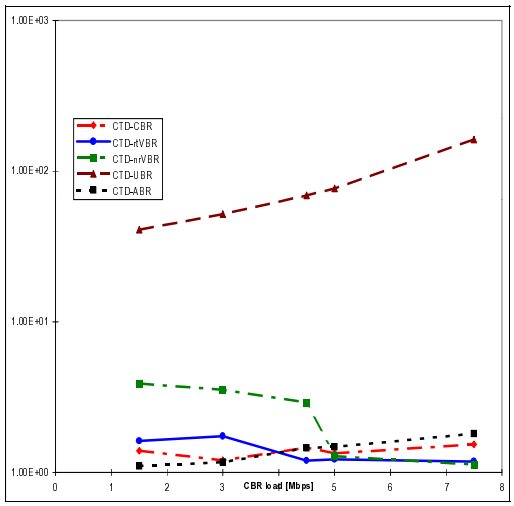


Fig. 4: Average Cell Transfer Delay

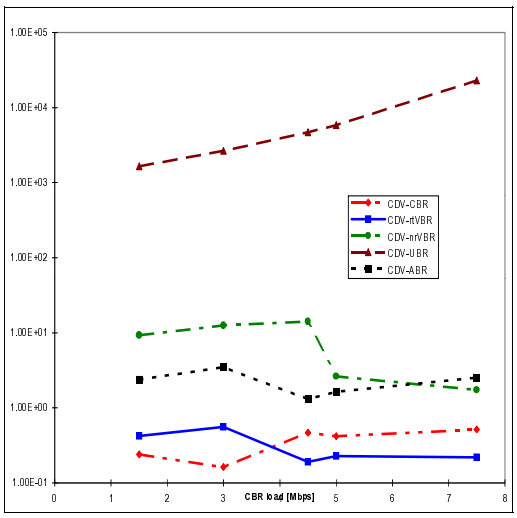


Fig. 5: Peak-to-Peak Cell Delay Variation