Bandwidth Allocation Based on Real Time Calculations Using the Convolution Approach

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ABSTRACT

This paper focusses on one of the methods for bandwidth allocation in an ATM network: the convolution approach. The convolution approach permits an accurate study of the system load in statistical terms by accumulated calculations, since probabilistic results of the bandwidth allocation can be obtained. Nevertheless, the convolution approach has a high cost in terms of calculation and storage requirements. This aspect makes real-time calculations difficult, so many authors do not consider this approach. With the aim of reducing the cost we propose to use the multinomial distribution function: the Enhanced Convolution Approach (ECA). This permits direct computation of the associated probabilities of the instantaneous bandwidth requirements and makes a simple deconvolution process possible. The ECA is used in Connection Acceptance Control, and some results are presented.

1. INTRODUCTION

The basic objective of a bandwidth management and traffic control strategy in ATM network is to allow for high utilization of network resources, while sustaining an acceptable QOS for all connections. In ATM, all the existing connections on a link are statistically multiplexed. Note that statistical multiplexing is efficient and allows more calls to enter the network than in the case of peak rate allocation, since it exploits the small probability that a larger number of calls will be active simultaneously [9] and [17].

It is possible to assign an equivalent bandwidth (effective bandwidth for some authors) to each source which reflects its characteristics. Several network traffic control functions such as congestion control and routing depend on the characterization of the equivalent bandwidth of individual connections and the resulting load on networks links. A major challenge is to provide traffic control functions in real-time. This normally involves a reduction in the complexity, and of course the accuracy, of the evaluation models.

The analytical approaches to the blocked probabilities are due to [10]. Other graphical results for source load are presented in [2] and [19]. At burst level two different approaches for equivalent bandwidth evaluation are studied by [7] and [6], in which different aspects of the behavior of multiplexed connections, fluid-flow model and stationary bit rate distribution are presented. The fluid-flow model is also studied by [2]. This model estimates the equivalent bandwidth when the individual impact of connections is critical, and it does not consider any multiplexing aspect. The fluid-flow model is valid when the buffer capacity is longer than the mean burst duration.

Our study focusses on the stationary model. In this case the effect of statistical multiplexing is the dominant factor, and it considers that all the excess cells are lost when the instantaneous rate is greater than the bandwidth provided by the link.

Several limitations have been found in the previous studies: a) only sources of two-state, ON-OFF sources are presented; b) accurate evaluations have been simplified in order to reduce the complexity of calculations and the memory, and in [7] the convolution approach is applied only as binomial distribution over homogeneous sources; c) no distinctions have been made applying different QOS to the individual connections; and d) all models studied describe the behavior of the sources without considering the interactions in the network. The impact of the sources is studied in an individual manner (fluid-flow model), or a statistical evaluation is applied to a set of sources (stationary model).

Our study has been carried out under the following premises:

1) In the ATM network the QOS involves not only the cell loss probability, but also the cell delay and jitter. Therefore, very large buffers cannot be introduced. We do not study the size of the buffer; it will be dimensioned by imposing that the cell loss probability will be negligible by contention at cell level.
2) Statistical multiplexing is the dominant factor. This occurs when a large number of connections share a link. Normally, the burstiness of the sources permits a statistical multiplexing gain.
3) According to points 1) and 2), the stationary model will be used in order to evaluate the bandwidth offered by all connections. More specifically, we choose the convolution approach, which is an extension of the binomial distribution.
4) When bandwidth evaluation is used in traffic control (CAC), the source model chosen and the evaluation algorithm chosen in 3) involve a computation complexity which makes real-time responses difficult. In order to reduce this high cost we present new methods of evaluation.
5) ATM must provide proper QOS for different service classes. QOS parameters include maximum cell delay, cell loss probability, maximum cell delay variation, etc. In this study no distinctions have been made between applying different QOS to the individual connections. Different QOS can be achieved using priorities [14], [11], [12] et al., but we do not introduce this aspect in our work.

One important aspect of Bandwidth Allocation is Connection Acceptance Control (CAC) application. CAC is the set of actions taken by the network at the call set-up phase (or during the call renegotiation phase) in order to establish whether a virtual connection can be accepted or has to be rejected [4]. The decision is based on the resources occupied by the existing connections and the

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characteristics of the new connection. The importance of equivalent CAC for achieving preventive control is widely recognized [20].

The most important requirements for the CAC function, presented in [15], [16], [2], [18] et al., are: resource allocation must meet QOS requirements for all established connections, which means that the network has to be protected from overload; the CAC should be able to function with a limited set of parameters that characterize the traffic, with fairness in distribution of blocking probabilities, and that can be enforced by a policing function; reasonable real-time processing and storage requirements are needed; and maximal statistical multiplexing gain should be obtained.

QOS is the most important aspect, and statistical multiplexing gain is just a desired benefit of ATM. Our work focusses, especially on reasonable real-time processing and storage requirements and maximizing statistical multiplexing gain. Obviously, all the methods studied guarantee QOS for all connections.

The convolution approach is the most accurate method used in CAC. But it has a considerable computation cost and a high number of accumulated calculations. Nevertheless, in critical near-congestion situations, the convolution is the only algorithm that gives enough accuracy. The objective of this study is to evaluate the usage requirements (complexity in terms of processor capacity and memory required to do the calculations) of bandwidth allocation based on the convolution approach. Two different implementations have been studied, the first based on the convolution expression (1), and the second based on the use of the Multinomial Distribution Function (MDF) (5).

This statistical multiplexing gain can only be achieved if the network knows the probability distribution density function of the individual sources. This study has been carried out according to the General Modulated Deterministic Process (GMDP) model, with which this model permits two state sources (ON/OFF), and more defined states can be modelled if it is necessary. Sources are grouped in types; a type of source has identical GMDP parameters.

The convolution is studied in Section 2; the MDF and its associated methods of calculation are analyzed in Section 3. Some results of Bandwidth Allocation using Enhanced Convolution Approach (ECA) are presented in Section 4. Some improvements for CAC based on the ECA are explained in Section 5.

2. ANALYSIS OF THE CONVOLUTION APPROACH

This section contains the calculation of the bandwidth requirements of the superposition of several sources. This approach is based on the convolution expression:

$$P(Y + New = b) = \sum_{k=0}^{b} P(Y = b - k) P(New = k) \qquad (1)$$

where Y is the bandwidth requirement of the already established connections; New is the bandwidth requirement of a new connection, and b denotes the instantaneous required bandwidth. In fact, the convolution approach obtains a probability density function for the offered system load, expressed as the probability that all traffic sources together are emitting at a giving rate.

The Convolution Approach assumes independent connections and does not take into account the duration of the corresponding burst. For short burst lengths, there is a certain multiplexing gain by buffering of bursts or parts of bursts. Hence, for short burst duration, this approach does not fully exploit the capacity of the ATM system. Provided network buffers are dimensioned properly, this approach offers a conservative allocation of bandwidth. The Convolution Approach overtimes the bandwidth requirements if the burst length is less than the buffer size of the multiplexer [15].

The direct application of (1) in order to evaluate the convolution is difficult in practice. Two data structures are necessary for an effective evaluation. Each type of source (j-type) has an associated Source Status Vector (Source-SV$_j$); this vector has two fields, rate and its associated probability, for each possible state. To store all the transmission rates possible for the connections established at a given moment, and to store the probability that the sources will emit at those rates, a System Status Vector (System-SV) is needed. This vector has the same two fields, rate and probability, as the Source-SV$_j$.

To evaluate the Convolution Approach, the following process is carried out: when a new connection is made, the System-SV must be updated. The corresponding Source-SV is used to make this update: for each old System-SV element a set of new System-SV elements is generated. The number of these elements is determined by the number of emission states possible from the new connection. The Rate of each new element is the sum of the existing rate and the rate corresponding to the state of the new source. The Probability of each new element is the product of the existing probability and the new probability corresponding to the state of the new source.

The implementation cost is evaluated as follows: let ST equal the number of types of sources, and CN_j is the number of j-type connections; let SN_j be the number of states of the j-type sources. The number of elements M necessary to store the System-SV is:

$$M = \prod_{j=0}^{ST-1} SN_j^{\,CNj} \qquad (2)$$

The same rate may appear more than once in System-SV. The size of the System-SV may be reduced by sorting and combining the repeated rates; the amount of reduction which can be achieved depends on the rates $r_{j,i}$ (rate of a j-type source emitting in i-state) of the source types and the number of states SN_j. The evaluation cost is proportional to the size M of the vector. M products and a sort of M elements are necessary.

There are two possibilities for the implementation of the above algorithm:

a) With storage: To overcome the computing time problem, one possibility is to store the bandwidth distribution of the total traffic stream. In this case only one convolution for a connection set-up and one deconvolution for a connection release is needed.

b) Without storage: The distribution is not stored. For connection set-up many convolutions (equal to the number of existing connections) have to be calculated but no deconvolution is needed for connection release.

The size of the storage required presents a bigger problem. Note the great amount of memory storage M required by the System-SV. This requirement increases with the number of connections CN and possible source states SN_j. The probability as expressed in the System-SV is the result of a large number of previous calculations. Furthermore, this process does not allow an easy deconvolution [21]. When there is a disconnection a deconvolution is needed for implementation a). For implementation b), in order to arrive at an exact calculation of the vector which would result from a connection release it is necessary to calculate from scratch. The time needed for the convolution increases with the number of states per connection. In implementation b) this time is greater because many convolutions have to be calculated.

3. THE ENHANCED CONVOLUTION APPROACH

We have studied a new, faster method for overcoming these drawbacks. As we have seen in the previous section, after convolution the same rate may appear more than once in the System-SV. Which elements are repeated? How many times? The next section tries to answer this questions for one type of source: homogeneous traffic.

We shall study the Multinomial Distribution Function (MDF) [1]. In this section we assume only one type of source, emitting in SN states. Each state-i has an associated rate r_i and probability p_i. Therefore, for CN connections cn_0 sources are in state S_0; cn_1 sources are in state S_1; and cn_{SN-1} sources are in state S_{SN-1}.

We can consider a SN dimensional random variable (S_0 , S_1 , ... , S_{SN-1}). Therefore, a random event that has been "repeated CN times (considering all the connections at a time) has the characteristic (cn_0, cn_1, ..., cn_{SN-1}). It is necessary to calculate the probability of S_0 occurring cn_0 times, S_1 occurring cn_1 times , and S_{SN-1} occurring cn_{SN-1} times. For this purpose we now consider generalized Bernoulli trials. As in the previous situation we assign to the point (S_0 , ... , S_0 , S_1 , ... , S_1 , ... , S_{SN-1} , ... , S_{SN-1}) with (cn_0, cn_1, ..., cn_{SN-1}) connections the probability

$$p_0^{cn_0} \cdot p_1^{cn_1} \cdots p_{SN-1}^{cn_{SN-1}} \qquad (3)$$

This is the probability assigned to any specific sequence having cn_i occurrences of S_i varying $i = 0, 1, \ldots, SN_j - 1$. Thus, the number of sequences having exactly cn_0 connections in state S_0, cn_1 connections in state S_1,.... and cn_{SN-1} connections in state S_{SN-1} is :

$$\frac{CN!}{cn_0!\,cn_1!\ldots cn_{SN-1}!} \qquad (4)$$

Finally, the probability of all sequences that have this characteristic is, according to [13]:

P(state S_0 occurs cn_0 times,... ,state S_{SN-1} occurs cn_{SN-1} times)=

$$\frac{CN!}{cn_0!\,cn_1!\ldots cn_{SN-1}!}\; p_0^{cn_0} \cdot p_1^{cn_1} \cdots p_{SN-1}^{cn_{SN-1}} \qquad (5)$$

When cn_0, cn_1, ..., cn_{SN-1} are non-negative integers whose sum is CN, this probability is called the MDF. Note that the probability of each source beginning in the state S_i is independent of the probability of the other source states.

The multinomial approach is applied to groups of the same type of sources, and the general state probabilities are evaluated by convolution of the partial results obtained from the different existing groups of sources.

Some data structures are necessary to evaluate the Enhanced Convolution Approach (ECA). For CN connections of the same type, there is an associated Sub-Matrix (SMX). SMX_r is the generic row of SMX. The number of columns in this element is equal to the number of source rates SN

$$SMX_r = < cn_0, cn_1, \ldots, cn_{SN-1} > \qquad (6)$$

SMX stores the distribution of the connections that there are in each state. The system load density function is obtained directly from the sub-matrix using the MDF (5). This sub-matrix has M rows; this value is the number of possible combinations of this type source, distributing CN objects (connections) into SN boxes (states). M depends on SN,

$$M_{SN}(CN) = \sum_{t=0}^{CN} M_{SN-1}(t) \text{ with } M_1(CN) = 1 \qquad (7)$$

Memory capacity and calculation requirements remain reasonable, even when considering models where more than three states per source are possible.
The associated rate of this row R_r is:

$$R_r = \sum_{i=0}^{NS-1} r_i \cdot cn_i \qquad (8)$$

and P_r is the probability of the SMX_r; it is evaluated directly with the MDF (5).

When there are different types of source j (non-homogeneous traffic), it is necessary to convolute between all source types. To store all possible combinations relating to the system state, a System Status Matrix (SSM) is defined. The generic elements of the SSM, namely the general system status rows SSM_r, are generated each by concatenation of all possible combinations between the different sub-matrices rows SMX_r, associated with the ST different j-types of sources (j=0, 1, ..., ST-1) :

$$SSM_r = < SMX_{r_0,0}, \ldots, SMX_{r_{ST-1},ST-1} > \qquad \forall r_j = 0, \ldots, M_j - 1; \qquad (9)$$

and from (6)

$$SSM_r = < cn_{r_0,0}, \ldots, cn_{r_0,SN_j-1}, \ldots, cn_{r_{ST-1},ST-1}, \ldots, cn_{r_{ST-1},SN_j-1} > \qquad (10)$$

It is not necessary to store either rate or the probability corresponding to each general state. The rate of each row of SSM is:

$$\mathrm{R_R} = \sum_{j=0}^{ST-1} \mathrm{R}_{j,r} ; \qquad \text{and the probability is:}$$

$$\mathrm{P_R} = \prod_{j=0}^{ST-1} \mathrm{P}_{j,r} \tag{11}$$

Given this system of calculation, results are obtained directly from each element and from there alone, unlike the convolution defined in Section 2, which obtains results by accumulation.

When a connection terminates, the state of the system must be updated. In implementation a), with storage, the bandwidth now occupied may be obtained by deconvolution. The fact that all possible state combinations relating to a given source type are contained within one sub-matrix means that source disconnection is simply a question of processing this sub-matrix: deconvolution. Deconvolution is essentially a means of evaluating the relative lightening of the system load after a disconnection.

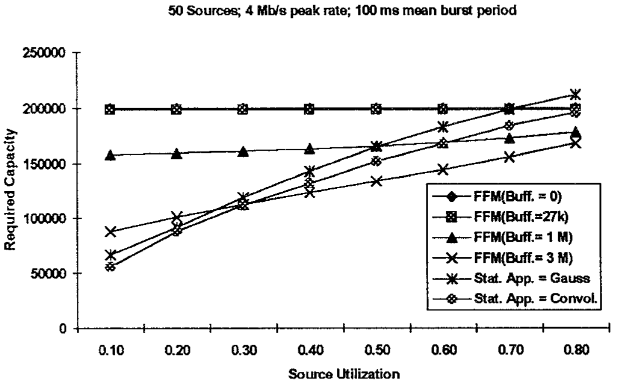
4. RESULTS OF BANDWIDTH ALLOCATION USING THE CONVOLUTION APPROACH

In [GUE], while the methodology proposed can provide an exact approach to the computation of the equivalent capacity, some approximations are required because the associated complexity makes it infeasible for real-time network traffic control applications. One approximation relies on a fluid-flow model (with buffer of 3M) and the other focusses on the distribution of the stationary bit rate on a link (Gaussion assumption). The two approximations overestimate the required capacity. The equivalent capacity is the minimum of the values obtained from both the flow and stationary approximations.

The figure examines the different capacity required for the fluid-flow model (FFM) with different buffer size, and stationary approximation for the Gaussian assumption and for the convolution.

The required capacity evaluated by convolution is always less than that required for the Gaussian assumption, but it is higher than that required for the fluid-flow approximation with a buffer of 3M when the source utilization is higher than 0.30. Futhermore, when the size buffer is 1M, the same only occurs when the source utilization is higher than 0.60. When using a small buffer, the convolution approach is always less.

Since the amount of computation has been reduced using the ECA it is not necessary to approximate the distribution of the stationary bit rate by a Gaussian distribution, and it is possible to improve an exact traffic control function in real-time.



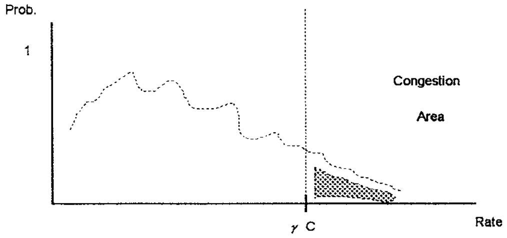
5. IMPLEMENTATION ISSUES FOR CAC BASED ON THE CONVOLUTION APPROACH

This section presents a set of mechanisms designed to improve the performance of the ECA when it is used for CAC. In CAC only a YES/NO response is necessary. With this improvement it is possible to improve these traffic control functions in real-time. For a detailed bandwidth distribution result, the cut-off calculations cannot be used because the evaluation algorithm does not examine all possibilities.

The Decision Criterion in order to accept a new connection of j-type when the ECA is used in CAC is:

$$\mathrm{PC(Y+New_j)} = \mathrm{P(Y+New_j} > \gamma.\mathrm{C}) = \sum_{b>\gamma.C} \mathrm{P(Y+New_j} = \mathrm{b}) < \varepsilon \tag{12}$$

Where PC is the Probability of congestion; Y is the Bandwidth requirement of the already established connections; Newj is the Bandwidth requirement of a new j-type connection; C is the physical link capacity; b is the Instantaneous Rate considered; ε is the maximum accepted Probability of Congestion due to excess bandwidth required, set according to the QOS requirements; and γ is the load factor that one has to pay regard to in order to limit congestion arising from contention resolution on the cell level. The maximum load is restricted to a predefined value γ. This has to be taken care of by a proper choice of γ. For the same reason the bandwidth provided by the link, and not the capacity of the link, determines the limit of excess. .



In the figure, the shaded area under the convolution distribution function and at the right of the value γC is the Probability of Congestion (PC); if this area is greater than ε the system is in Congestion.

The Balanced Algorithm combines appropriate storage requirements with low calculation cost. In the zero storage requirement, option memory is saved but there is a considerable calculation cost. Finally, we present cut-off calculations as an option for achieving faster implementation.

Balanced Algorithm.

The stored bandwidth allocation option requires a considerable amount of memory and a high number of calculations. In the general SSM the repeated sub-matrices correspond to the same associated calculations. To reduce these drawbacks, partial results can be stored in a set of vectors associated with each type of source. It is therefore not necessary to store all the SSM: storing SMX for each type of source is enough.

Enhanced Balanced algorithm. In this method each partial probability corresponding to a type of source is evaluated by using the MDF and is stored in an associate vector PV. This vector stores rate and its associated probability for all possible combinations in a sub-matrix SMX. Therefore, the associated probability for any rate is the result obtained from the pre-stored values: convolution of sub-matrices.

Sorted & Compacted Balanced Algorithm. Unfortunately, the multinomial distribution function does not detect identical rates from additions of different partial values. In order to solve this problem the sub-matrix must be sorted and compacted. Therefore, the PV vector is first sorted and later compacted like the convolution algorithm presented in Section 2. The most important aspect of this algorithm is the fact that the process is applied only to a sub-set of the system status, (i.e. a PV vector corresponding to a type of source), and the amount of calculation is reduced.

Zero storage requirements

The total Probability of Congestion (PC) of the system allows evaluation without storing pre-evaluated values. The partial probability corresponding to a row of the System Status Matrix is evaluated independently; then this partial value is added to the partial PC. For this evaluation, it is necessary to ensure that all the elements are generated in the appropriate order to obtain all the possible combinations. The main drawback of this option is the considerable number of calculations required. Therefore, this option is not recommended for real time evaluation.

Cut-off calculations

Maximum Rate Cut-off. A further reduction in calculation cost is obtained as follows: calculation of probability is only carried out in cases where the associated rate exceeds the bandwidth provided, $\gamma .C$. Note that the calculation of probability is considerably more complex than the calculation of rates, so we select the objects for our calculation on the basis of the latter.

Partial Sorting. Furthermore, in each block, the rows generated are not examined at random, but are graded according to rate, so when the pre-set minimum rate C is reached, in each SSM the rows generated are not examined in an arbitrary order (e.g., as they are, one after the other), but are graded according to rate, so when the pre-set minimum rate $\gamma .C$ is reached the process is terminated, and a further saving is achieved.

Probability of Congestion Cut-off. In CAC methods the process of evaluation has one clear aim: to indicate whether or not a new connection will be accepted. For this decision the Probability of Congestion of the System is compared with a previously set value, in order to guarantee a specific QOS. Therefore, if during the process of calculation the accumulated PC exceeds a previously set value, the process can be stopped, and the calculation cost is thus reduced.

Results

Given a system with 40 connections of 0-type and 4 connections of 1-type, both with three states, the next table shows the number of calculations and the number of elements necessary to calculate the bandwidth allocation in the ECA. The bandwidth provided by the link γC is 150 MBit/s, and $PC < \varepsilon = 10\text{-}4$ is the decision criterion.

CALCULATION OPTIONS	Eleme n.	+	*	/	exp
CONVOLUTION BASED ALGORITHM(*)	873	634,728	317,298	0	0
ENHANCED CONVOL. APPROACH(**)	12,915	322,875	180,810	25,830	25,83
ZERO STORAGE	0	322,875	180,810	25,830	25,83
ENHANCED BALANCED ALGORITHM	876	31,086	23,427	876	876
Sorted & Compacted BALANCED A.(*)	876	6,606	11,184	876	876

(*) Sorted and Compacted. A supplementary cost depending on the amount of the elements is needed in these cases.
(**) These values are presented in order to compare with the other implementations.

6. CONCLUSIONS

This paper is concerned with improving the performance of the Convolution Approach by application of the MDF to store groups of the same source type; general state probabilities are evaluated by the convolution of partial results obtained from the existing groups of sources.

When the Enhanced Convolution Approach (ECA) is used to study the system load, numerical results show reasonable evaluation cost and storage requirements. If the ECA is used in CAC algorithms, real-time evaluation is possible.

In CAC the ECA offers performance hitherto associated with two-level processes. In the current stage of development of the model, peak-rate analysis fulfils classical first-level functions, with convolution analysis corresponding to a second level. In the future our work will try to further enhance the convolution approach by developing a more sophisticated, more progressive method of system load evaluation.

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