A Global Control System for Integrated Admission Control and Routing in ATM Networks

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Abstract.- In this paper a global control system for admission control, routing and bandwidth allocation in the ATM environment is presented. The traffic is divided into classes, characterized by statistical parameters and by Quality of Service (QoS) requirements, as the rates of lost and delayed cells. At connection set-up, a strategy decides if a connection request has to be accepted or rejected and which is the best route that all the cells of that connection have to follow. The decision about acceptance guarantees the QoS requirements for each class, while the routing strategy is aimed at minimizing the number of blocked calls in the network. The whole system provides also a mechanism to achieve a fair and adaptive bandwidth allocation for each traffic class; the bandwidth allocation control has a longer intervention period than the admission and routing control. In fact, the global strategy can be regarded as a hierarchical one. Several simulation results are reported, to verify the effectiveness both of the admission and routing mechanism and of the allocation strategy.

I. INTRODUCTION

Asynchronous Transfer Mode (ATM) networks, by statistically multiplexing many types of traffic sources at the cell level, with different performance characteristics and traffic parameters, certainly allow a great flexibility in the allocation of network resources and simplify the switching mechanisms needed to handle such heterogeneous flows.

On the other hand, the need of guaranteeing contracted Quality of Service (QoS) requirements for each connection in the absence of guaranteed bandwidth allocation, especially in the presence of many bursty sources with different statistical nature, raises many and often unsolved problems. In a way, the flexibility and simplicity in traffic handling within the network brings along a large amount of controls, to be exerted mainly at the network boundaries (but, to a certain extent, also within the network) on the dynamic allocation of resources.

Actually, the above is generally true for all multiservice networks; however, the ATM environment is particularly affected by the need of dynamic control mechanisms, which can be located at various levels of traffic characterization (e.g., cell and call level): congestion and admission control, scheduling mechanism, routing control at call connection, fair allocation of resources (like bandwidth and buffers) among different service classes are just a few examples.

Each of the topics listed above has received a great deal of attention in the literature: [1-4], among others, deal with bandwidth allocation; [5-10] consider call admission and congestion control; [11, 12] propose fair scheduling mechanisms, while the routing strategy has been treated extensively in [13, 14] and many others. Some aspects have often been treated in a combined way, as in [15-22]. As is often the case in large scale systems, characterized by the presence of dispersed information, computation and transmission delays, a dynamic hierarchical control structure can be envisaged [23], at least for some control tasks; this approach has been adopted, in a different context, also in [24, 25].

The aim of the present work is to propose a global scheme for call admission control and routing in the ATM environment, capable of guaranteeing QoS requirements for each traffic type in the network and a fair management of network resources, by a dynamic hierarchical two-level control mechanism. The traffic is considered to be divided into classes, characterized by statistical parameters, like peak bandwidth and burstiness, and by performance requirements, like lost and delayed cell rates. An admission control and routing scheme (lower level) is dedicated to each specific class upon connection request; at the higher level, a resource allocation procedure manages a fair division of the available bandwidth between the traffic classes. The cell scheduling strategy depends on the capacity partitions decided upon by the bandwidth allocator, and an output buffer for each traffic class is implemented. The routing decisions are determined by means of a distributed computational structure.

The paper is organized as follows. In the next Section, we describe the overall network and control architecture and the traffic model adopted. The bandwidth allocation procedure is presented in Section III, while the routing procedure is described in Section IV. A simulative analysis of the effectiveness of the proposed control system is given in Section V. Section VI contains the conclusions.

II. NETWORK, CONTROL SYSTEM, AND MODELS OF TRAFFIC SOURCES

We consider an ATM network composed by N nodes, connected by bi-directional links (the bi-directional hypothesis can be relaxed by having, for example, dedicated control channels on reverse directions). The traffic is supposed to be divided into H classes, where each class differs from the others for the required QoS, in terms of cell loss and delayed cell rate, and for statistical properties, such as average and peak bandwidth. We distinguish two kinds of nodes, namely, access and transit nodes. Access nodes are simple access points,

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directly connected to the user, with possible multiplexing functions. Transit nodes have the structure depicted in Fig. 1. These nodes are composed by three basic elements: the Switching Element, the Routing and Admission Controller (RAC) and some Controlled Multiplexers (CM). The node structure and its components are used only with the purpose of outlining a general control scheme for bandwidth allocation, access control and routing. As shown in Figure 1, we suppose an ATM switching element having inputs coming from other nodes, transit or access ones, and one input coming from the RAC. Each outgoing port of the switching element sends cells to a CM, connected to an access or a transit node through an outgoing link ij of capacity $C^{(ij)}$ Mbits/s. Due to the assumption of bi-directional links, the node has the same number of inputs and outputs.

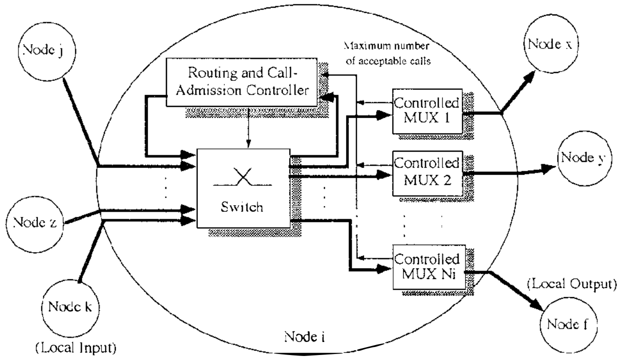

Fig. 1. Network and node structure.

The structure of a generic CM is shown in Fig. 2. The incoming traffic from the switch is divided among the classes, and the cells of each class h, $h=1,\dots,H$ are sent to a different buffer of finite length $Q^{(h,ij)}$, where ij is the link connected to the CM. All the queues are served by a flexible multiplexer, by assigning each buffer a portion of the total bandwidth available on the outgoing links. The goal of the bandwidth allocation controller in each CM is to recompute, periodically, two sets of quantities: the capacity shares $V_m^{(h)}$ $h=1,\dots,H$ (where m is a time instant defined in Section 3 below) used by the scheduler, and the maximum number of acceptable connections per class for that link. The assignment of new bandwidth partitions is made on the basis of the dynamic variations in the traffic flows, with the goal of providing a fair sharing among different classes. The maximum number of acceptable connections is computed for each class on the basis of the assigned bandwidth and then passed along to the RAC by all CM's. In this way the RAC knows, at every instant, how many calls can be accepted for each link and each class on that link.

The function of the RAC is to decide, at connection set-up, if a call can be accepted and which is the outgoing link it has to be routed onto. We suppose that every time a user wants to open a connection, the user sends a special packet, called Resource Reservation Packet (RRP). When a switching element receives a RRP from the local input or from another node, it forwards this packet to its RAC. The RAC verifies if there is place for a new connection of the requiring class (i.e., if the number of connections in progress is less than the maximum acceptable number) on a sub-set of outgoing links, belonging to the set of possible paths for the required destination. If one or more links are available, the RAC uses a routing algorithm, described in the following Section, to choose one of the outgoing links and then reserves the needed resources on the link chosen. Moreover, it sends a new RRP packet to the next node in the path. Otherwise, if there is no place, the RRP is changed into a Free Resource Packet (FRP), which is sent back by the switch along the path already done by the corresponding RRP. When a switching element receives a FRP, the same FRP is sent to the RAC, which releases the resources already reserved for the calls related with it. It is clear that every RAC has to support the number of connections in progress at all instants for every class and output links.

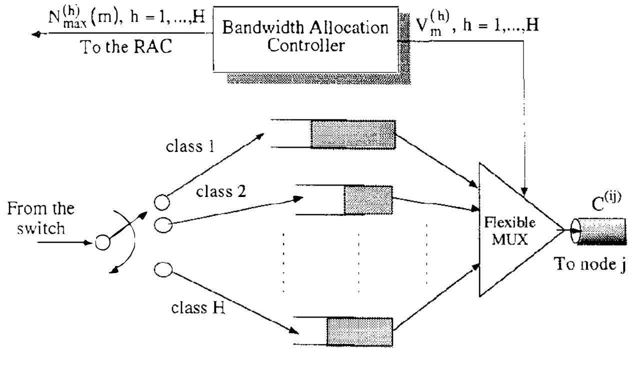

Fig. 2. Structure of the Controlled Multiplexer (CM).

To derive the appropriate strategies to be applied by the RAC and by the allocation controller in the CM's, we first need to characterize a model of traffic sources. As regards class h traffic, we suppose it to be made up by bursty connections (on-off sources) with identical and mutually independent statistical characteristics. Each bursty connection is represented by means of a two-state model (active and idle, respectively). The transitions between these states form a two-state Markov chain, and we denote by $\alpha^{(h)}$ and $\beta^{(h)}$ the probabilities of transition from the idle to the active state, and from the active to the idle state, respectively. For each traffic class, these probabilities can be easily derived as in [7], if we suppose the statistical characteristics of the traffic flow to be known. Moreover, in order to take into account sources at different speed, we assume that, during a slot interval, an active connection may generate a cell with probability

$$r^{(h,ij)} = \frac{P^{(h)}}{C^{(ij)}} \qquad (1)$$

i.e., corresponding to the ratio between the peak bit rate $P^{(h)}$ at which an active call generates bits and the speed of the channel $C^{(ij)}$. Of course, when a connection is idle it does not generate cells. The steady-state probabilities of a connection being idle and active, respectively, are

$$w_{idle}^{(h)} = \frac{\beta^{(h)}}{\alpha^{(h)} + \beta^{(h)}} \qquad w_{act}^{(h)} = \frac{\alpha^{(h)}}{\alpha^{(h)} + \beta^{(h)}} \qquad (2)$$

Let $N^{(h)}$ be a given number of multiplexed connections; as they are independent of each other, the steady state probability $V^{n^{(h)}}_{N^{(h)}}$ of having only $n^{(h)}$ active connections out of $N^{(h)}$ network connections is given by

$$v^{n^{(h)}}_{N^{(h)}} = \binom{N^{(h)}}{n^{(h)}} \left(w_a^{(h)}\right)^{n^{(h)}} \left(w_i^{(h)}\right)^{N^{(h)}-n^{(h)}} \tag{3}$$

III. BANDWIDTH ALLOCATION PROCEDURE

In this Section, we consider only a single CM in a generic node i, connected to link ij; for the sake of simplicity, we drop the index *ij* from the notation (h, ij). We take the transmission time of a cell at the line speed C as the discrete time unit (slot) and, in the following, k denotes the discrete time variable.

The first goal of the RAC is to divide the total capacity C of the outgoing links (in Mbits/s) into "virtual" capacities $V_m^{(h)}$, h=1,...,M, where m=0, K, $2K$,... represent the instants at which the reallocation is performed and K is the length of the intervention period (in slots), whose choice is briefly discussed in Section 5. The m-th assignment holds constant for the time between two consecutive reallocation instants, that is for k=m, m+1, ..., m+K-1. To reach the reallocation goal, a suitable cost function, that takes into account the expected number of lost cells, pertaining to the whole offered traffic over the following K slots, is minimised at each instant m, where a new K-slot period begins. The second goal consists in computing, once fixed the $V_m^{(h)}$ values, the maximum number of connections per class $N_{\max}^{(h)}(m)$ that can be accepted without exceeding the QoS constraints.

To reach these goals, two performance indeces are taken into account: the average cell loss rate $R_{loss}^{(h)}\left(N^{(h)},V_m^{(h)}\right)$ and the average delayed cell rate $R_{delay}^{(h)}\left(N^{(h)},V_m^{(h)}\right)$, where $N^{(h)}$ is the number of class h connections in progress.

To keep our derivation analytically tractable, and to allow the use of a first order descent method in the minimization to be performed for the capacity reallocation, we have chosen, in this paper, not to assign the buffer lengths $Q^{(h)}$ dynamically; they are determined a priori (off-line) and never changed.

Since, due to our previous assumptions, each traffic class effectively "sees" a virtual multiplexer with buffer length $Q^{(h)}$ and channel capacity $V_m^{(h)}$, we can derive $R_{loss}^{(h)}\left(N^{(h)},V_m^{(h)}\right)$ and $R_{delay}^{(h)}\left(N^{(h)},V_m^{(h)}\right)$ for each single virtual multiplexer, independently of the others.

Let us consider the cell loss rate, which can be computed as

$$R_{loss}^{(h)}\left(N^{(h)},V_m^{(h)}\right) = \sum_{n=0}^{N^{(h)}} r_{loss}^{(h)}\left(n,V_m^{(h)}\right) v^{n}_{N^{(h)}} \tag{4}$$

where

$$r_{loss}^{(h)}\left(n,V_m^{(h)}\right) = \sum_{i=0}^{Q^{(h)}} \frac{\sum_{j=0}^{n} \max\left(i+j-Q^{(h)},0\right) f_j^{(h)}(n)}{n\Gamma^{(h)}} \Pi_i^{(h)}\left(V_m^{(h)}\right) \tag{5}$$

represents the steady-state value of the "instantaneous" (in the sense of [7]) cell loss rate, n connections being in the active state. In (5), $\Pi_i^{(h)}\left(V_m^{(h)}\right)$, h=1,...,M, represents the steady state probability of having i cells inside the buffer and $f_j^{(h)}(n)$ is the probability of having j connections of traffic class h generating a cell with n connections of the same class in the active state, as computed in [7, 19 and 20].

Using the stationary distributions $\Pi_i^{(h)}\left(V_m^{(h)}\right)$, i=0, 1,..., $Q^{(h)}$ and $v^n_{N^{(h)}}$, n=0,...,$N^{(h)}$, entails a quasi-stationary approximation, which is suggested by the large difference in time scales between the cell and the burst dynamics. A similar type of approximation, though in a different context, is introduced in [26], where its validity is also carefully analyzed.

As concerns the delayed cell rate $R_{delay}^{(h)}\left(N^{(h)},V_m^{(h)}\right)$, it can be computed in a similar way as shown for the cell loss rate; the details can be found in [19].

The virtual capacities $V_m^{(h)}$ are dynamically reassigned by the allocation controller by means of a procedure that minimizes a suitable cost function. The function to be minimized is chosen to take into account the expected number of lost cells up to the next decision instant.

To this aim, by assuming the quasi-stationarity of the connection request processes over the K slot decision interval, the structure of the cost function has been taken as

$$J_m\left(V_m^{(1)},\ldots,V_m^{(H)}\right) = \sum_{h=1}^{H} \sigma^{(h)}\left[R_{loss}^{(h)}\left(\overline{N}_{acc}^{(h)}(m),V_m^{(h)}\right) + \xi\left(R_{loss}^{(h)}\left(\overline{N}_{tot}^{(h)}(m),V_m^{(h)}\right) - R_{loss}^{(h)}\left(\overline{N}_{acc}^{(h)}(m),V_m^{(h)}\right)\right)\right] \tag{6}$$

where the constants $\sigma^{(h)}$, h=1,...,H, are weighting coefficients, ξ is a trade-off coefficient, $\overline{N}_{acc}^{(h)}(m)$ is the average number of calls in progress measured during the interval $[m, m+K)$ and $\overline{N}_{tot}^{(h)}(m)$ the offered load measured during the same interval. Then, the first quantity in square brackets represents the cell loss rate with the same number of calls in progress as in the previous reallocation interval, while the second one represents the further loss rate that would have been incurred if also the refused calls had been accepted in the system.

Thus, the trade-off coefficient ξ can be used to increase the importance of call refusals that are not explicitly taken into account. As regards the choice of the weighting coefficients $\sigma^{(h)}$, it can be made in order to reflect the relative importance attributed to the various traffic classes by the network manager and the possibly largely different scales of loss probabilities.

In the minimization of the cost function (6), an equality constraint and a set of inequality constraints must be taken into account, namely

$$\sum_{h=1}^{H} V_m^{(h)} = C; \qquad V_m^{(h)} \ge V_{\min}^{(h)}\left(N_m^{(h)}\right) \quad h=1,\dots,H \tag{7}$$

where $N_m^{(h)}$ is the number of calls in progress at instant m for class h and $V_{\min}^{(h)}\left(N_m^{(h)}\right)$ is the minimum capacity needed to assure the required QoS.

To compute the values $V_{\min}^{(h)}\left(N_m^{(h)}\right)$ $h=1,\dots,H$, we need to fix the QoS precisely. The QoS's are defined for each class by fixing three parameters: $\varepsilon^{(h)}$, $\delta^{(h)}$ and $D^{(h)}$. $\varepsilon^{(h)}$ is an upper limit on the long-term time-averaged value of cell loss rate: if $N^{(h)}$ is the number of connections in progress and $V^{(h)}$ the capacity, we must have

$$R_{loss}^{(h)}\left(N^{(h)}, V^{(h)}\right) \le \varepsilon^{(h)} \tag{8}$$

$\delta^{(h)}$ has the same meaning for the long-term time-averaged value of the rate of cells that suffer a delay longer than $D^{(h)}$, that is

$$R_{delay}^{(h)}\left(N^{(h)}, V^{(h)}\right) \le \delta^{(h)} \tag{9}$$

By letting $N^{(h)} = N_m^{(h)}$, $h=1,\dots,H$, $V_{\min}^{(h)}\left(N_m^{(h)}\right)$ can be computed as the minimum value of $V^{(h)}$ that satisfies both (8) and (9). The minimisation of (6) under constraints (7) is a mathematical programming problem that can be performed by means of a gradient projection method [19, 20].

As concerns the quantities $N_{\max}^{(h)}(m)$, $h=1,\dots H$, which determine the call acceptance control rule (i.e., accept a new call request of class-h arriving in the interval $[m, m+K-1]$ if the number of class-h connections in progress plus one is less than or equal to $N_{\max}^{(h)}(m)$), they can be found in a similar way as $V_{\min}^{(h)}\left(N_m^{(h)}\right)$. In fact, $N_{\max}^{(h)}(m)$, h=1,...H, can be computed as the maximum value of $N^{(h)}$ that satisfies both (8) and (9), by fixing $V^{(h)} = V_m^{(h)}$. Note that the values $N_{\max}^{(h)}(m)$, $h=1,\dots,H$, are computed by taking into account performance requirements related with a single node and not with the whole path done by the cells of a connection. By now, this limitation is taken over by considering, in the routing procedure, only paths with length (in number of nodes traversed) less than or equal to a fixed quantity P, supposing that, at least, one of these paths exists for every source-destination pair. In this case, it is sufficient to divide the global performance requirements for each class by P to find the node requirements and assure the minimum required QoS along all the possible paths.

IV. ROUTING PROCEDURE

The routing procedure applied by a RAC is based on the computation of a cost function related to each link and composed by the weighted sum of a local and an aggregate quantity. Let i be the node considered; we define the "global" cost of link ij at instant k as

$$w_k^{(h,ij)} = w_{loc}^{(h,ij)}(k) + \alpha_j w_{agg}^{(h,j)}(s) \tag{10}$$

where $w_{loc}^{(h,ij)}(k)$ represents the "local" cost of link ij, $w_{agg}^{(h,j)}(s)$ the aggregate cost of node j, computed at time instant $s < k$, and α_j is a weighting coefficient. The main idea is to use the local cost to take into account the current condition (with respect to a measure that will be specified below) of the directly connected (to node i) link ij, whereas the aggregate cost has to summarise the network conditions beyond link ij. Since every node has to communicate $w_{agg}^{(h,j)}(s)$ to its neighbours, this value cannot be updated continuously, but we suppose it to be communicated only at some instants $s=T, 2T, \dots$ where T is an integer number of time slots. Although we have chosen a periodic update (as in the case of the reallocation instants m), s could be asynchronous; for example, each node could send $w_{agg}^{(h,j)}(s)$ to its neighbours every time its value changes significantly (i.e., the difference between two values taken at consecutive time intervals is above a specified threshold).

At time k, let $N_k^{(h,ij)}$ be the number of connections in progress for class h on link ij; we define the local cost of link ij and class h at instant k as

$$w_{loc}^{(h,ij)}(k) = \begin{cases} \dfrac{1}{N_{\max}^{(h,ij)}(m) - N_k^{(h,ij)}} & if\ N_{\max}^{(h,ij)}(m) > N_k^{(h,ij)} \\ Z & if\ N_{\max}^{(h,ij)}(m) = N_k^{(h,ij)} \end{cases} \tag{11}$$

where $k \in [m, m+K-1]$, and Z is a very large value. Thus, the local cost value is inversely proportional to the available space, in terms of the number of acceptable connections on the link, and it is Z when there is no more bandwidth available for class h, i.e., when no other calls of class h can be accepted on that link.

The aggregate cost of a generic node i is defined as

$$w_{agg}^{(h,i)}(s) = \overline{w}_{loc}^{(h,i)}(s) + \beta_i \overline{w}_{agg}^{(h,i)}(s) \tag{12}$$

where $\beta_i \in [0, 1]$ is a weighting coefficient and

$$\overline{w}_{loc}^{(h,i)}(s) = \frac{1}{L_i} \sum_{j \in dir(i)} w_{loc}^{(h,ij)}(s) \tag{13}$$

$$\overline{w}_{agg}^{(h,i)}(s) = \frac{1}{L_i} \sum_{j \in dir(i)} w_{agg}^{(h,j)}(s-T) \tag{14}$$

represent the local and the aggregate cost, respectively, averaged over the L_i directly connected nodes (whose set is indicated with dir(i)).

Note that $\overline{w}_{agg}^{(h,i)}(s)$ has to be computed with the data already available at the node, so that the farther the information comes from, the older it is. On the other hand, the importance of remote aggregate information can be weighted by using the coefficients α_i and β_i. More precisely, α_i can be used to balance between the local and aggregate parts of the cost, while β_i can be used to reduce or increase the influence of the most distant information. The routing scheme will be indicated as DLCP (Distributed Least Congested Path) in the following.

The access control and routing procedure are as follows. The RAC maintains a list of the links and their corresponding $w_k^{(h,ij)}$ values, in non decreasing order, and a set l^d for each possible destination d, containing the links along paths to the destination which are shorter than a certain fixed length (in number of hops). When the RAC receives a RRP whose requested destination is $\hat{d}$, it scans the list, and stops at the first link $\hat{ij}$ with $\hat{j} \in l^{\hat{d}}$. If $w_k^{(h,\hat{ij})}=Z$, the connection request is refused and a FRP is sent back to release the already allocated resources; otherwise the connection is accepted and resources reserved on the link $\hat{ij}$. In the latter case, $w_k^{(h,\hat{ij})}$ is updated, by adding 1 to $N_k^{\left(h,\hat{ij}\right)}$, and it is placed in the list in the correct position; then, a new RRP is sent to node $\hat{j}$. The entire list has be to rebuilt at instants s and m.

V. PERFORMANCE EVALUATION OF THE ADMISSION CONTROL AND ROUTING SCHEME BY SIMULATION

This Section is divided into two parts: the first one is aimed at testing the efficiency of the admission control mechanism, while the second one is oriented to give some indications about the behaviour and the performance of the proposed routing scheme. The results obtained are compared with other possible routing strategies.

We have based our simulations on the following data:

$C = 150$ Mbits/s; $H = 3$; T_s = slot duration = $2.83 \cdot 10^{-6}$ s

$P^{(1)} = 1$ Mbit/s; $P^{(2)} = 2$ Mbits/s; $P^{(3)} = 10$ Mbits/s

(peak bandwidth)

$b^{(1)} = 2$; $b^{(2)} = 5$; $b^{(3)} = 10$

(burstiness, defined as the ratio of peak to average bandwidth)

$B^{(1)} = 100$; $B^{(2)} = 500$; $B^{(3)} = 1000$ cells

(average burst length)

$1/\mu^{(1)} = 20$ s; $1/\mu^{(2)} = 15$ s; $1/\mu^{(3)} = 25$ s

(average connection duration)

$\varepsilon^{(1)} = \varepsilon^{(2)} = \varepsilon^{(3)} = 1 \cdot 10^{-4}$

(upper limit for the average cell loss rate)

$\delta^{(1)} = \delta^{(2)} = \delta^{(3)} = 1 \cdot 10^{-3}$

(upper limit for the average delayed cell rate)

$D^{(1)} = 400$; $D^{(2)} = 200$; $D^{(3)} = 100$ slots (delay threshold)

$N_a^{(1)}=80$; $N_a^{(2)}=100$; $N_a^{(3)}= 40$ Erlangs

(global average traffic intensities offered to the network; call arrival processes follow independent Poisson distributions)

$Q^{(1)} = 20$; $Q^{(2)} = 15$; $Q^{(3)} = 10$ cells (buffer length)

Fig. 3 shows the maximum number of acceptable connections (class 1), computed by the access rule; the result is compared with the real maximum number of acceptable calls obtained by simulations (10^8 slots each) and with the same quantity obtained by allocating each call its peak ($P^{(1)}$) and average bandwidth ($P^{(1)}/b^{(1)}$). The same graph is depicted in Figs. 4 and 5, concerning traffic classes 2 and 3, respectively.

It can be noted that values derived from the access rule are close to the real maximum values for traffic classes 1 and 2, while a very good efficiency is reached for traffic class 3.

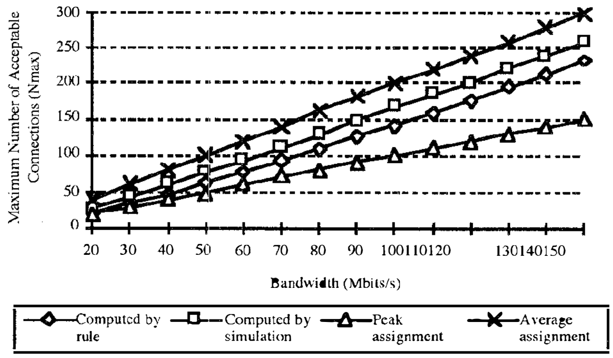

Fig. 3. Maximum number of connections vs. allocated capacity (class 1).

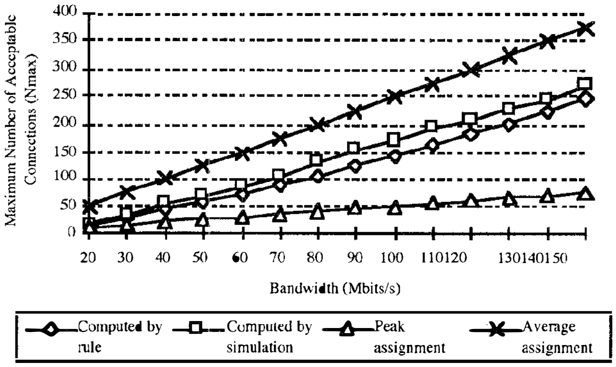

Fig. 4. Maximum number of connections vs. allocated capacity (class 2).

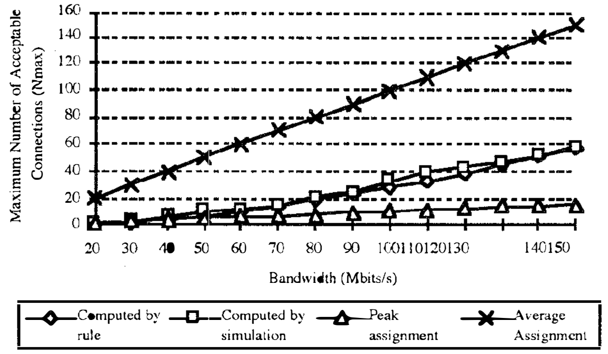

Fig. 5. Maximum number of connections vs. allocated capacity (class 3).

The second part of this Section is dedicated to the routing scheme, which is tested and analyzed by using the same data at the beginning of the Section (with $N_a^{(1)}=120$; $N_a^{(2)}=100$; $N_a^{(3)}= 15$ and $K=8 \cdot 10^7$ cells) in the twelve-node network depicted in Fig. 6 (only node 11 is a destination).

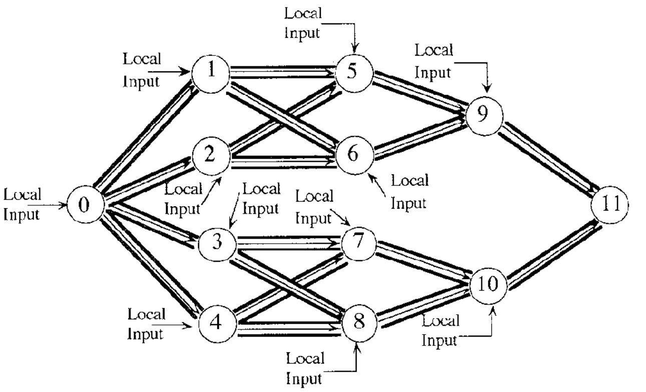

Fig. 6. Topology of the test network.

The traffic flow generated by the above data is considered to be a "normalized offered load" of value 1; an offered load "x" corresponds to the same data, except for the traffic intensities $N_a^{(h)}$, h=1, 2, 3, which are multiplied by x. The coefficients α_i and β_i, i=0,...,11, are the same at each node, that is, $\alpha_i=\alpha$ and $\beta_i=\beta$, $\forall i$.

The results presented in the following are intended to investigate the sensitivity of the system to parameters α and β, in order to show the importance of a careful updating procedure and weighting of the global cost and of the aggregate information. The best results obtained are then compared with two other routing strategies, which may be regarded as two extreme situations with respect to the use of information for routing purposes, namely, a centralized shortest path (SPR) and a totally decentralized "hot-potato" strategy.

All the simulations have a duration of 678.4 s, corresponding to 3 reallocation intervals, i.e., a bandwidth reallocation every 226.13 s.

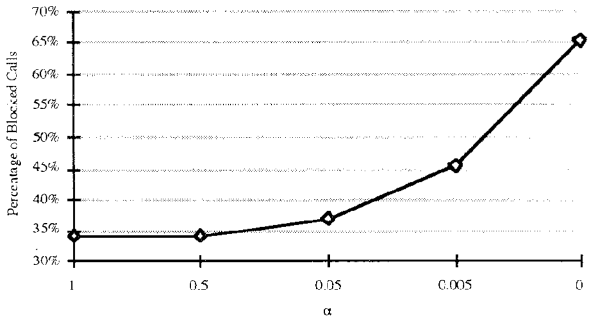

Fig. 7. Percentage of blocked calls vs. coefficient α.

Fig. 7 shows the total percentage of blocked connections versus the weighting coefficient α; to stress the effect of weighting the global cost, a bottleneck has been created in nodes 1 and 2, by reducing the channel capacity of each of their outgoing links to 25 Mbits/s, and by dividing the global offered load as follows: 37.5% to node 0, 31.25% each to nodes 1 and 2, and no load for the other nodes. The effect of the coefficient should be made clear by the graph: when α has a value close to 1, the network, however saturated, is aware of the bottleneck in nodes 1 and 2 and avoids critical nodes, by choosing the other branch; by decreasing the value of α, the network looses the awareness of critic nodes, down to a fully "blind" situation (α=0), resulting in drastic increasing the percentage of blocked calls.

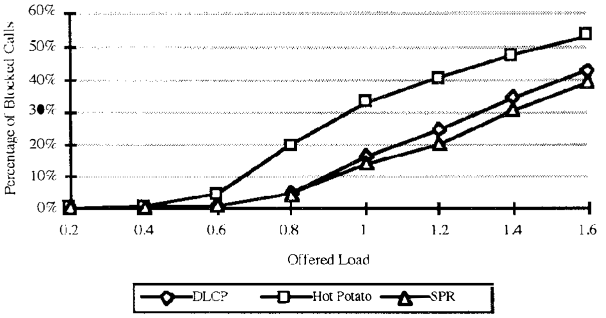

Fig. 8. Percentage of blocked calls vs. offered load.

Fig. 8 depicts the total percentage of blocked calls versus the offered load. The DLCP routing, with α=1 and β=1, is compared with a SPR strategy, where the cost of each link is the same as in (13), and with a local Hot Potato strategy, which is considered as a possible lower bound on performance. The percentage of blocked calls for DLCP is quite close to that of SPR.

VI. CONCLUSIONS

A global combined strategy for dynamic bandwidth management, admission control and routing in ATM networks has been considered in the paper. The strategy is based on a two-level dynamic hierarchical control architecture, consisting of a central bandwidth allocation controller, and as many call admission controllers as the service classes envisaged for the characterization of the user traffic.

The routing algorithm is embedded within this structure, and is based on a distributed computational procedure, which employs real time and aggregate delayed information on the status of the links in the network, in terms of number of connections in progress. Analytical and simulative performance analyses of the admission control rule have been reported, showing a rather efficient behaviour. Simulations showing the routing procedure have been also reported and discussed.

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