ABSTRACT

The statistical multiplexing operation within an ATM network node is considered, with respect to different methods for the allocation of the bandwidth of an outgoing link. Service separation is assumed by dividing the overall traffic flows into classes, homogeneous in terms of performance requirements and statistical characteristics, which share the bandwidth of a link according to some specified policy. This context allows one to clearly define, by means of several existing approaches, a region in the space of connections of the different classes (call space) where quality of service (QoS) requirements at the cell level are satisfied. Within this region, some criteria for allocating the bandwidth of the link to the service classes are proposed, and the resulting allocation and call admission control (CAC) strategies are defined and analyzed. The goal of these operations is to achieve some desired QoS at the call level. Several numerical simulation results are presented, in order to highlight the different performance characteristics of the various methods.

Bandwidth Allocation and Admission Control in ATM Networks with Service Separation

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The multiservice structure of broadband networks, where quality of service (QoS) requirements with possibly very different characteristics must be satisfied for traffic flows with different statistical natures, has led to the application of specific control actions whose main goals consist of maintaining the desired QoS levels and maximizing the utilization of network resources (or some revenue function). This feature, being connected to service integration, is not necessarily related to asynchronous transfer mode (ATM), but it is present in time-division multiplex (TDM) networks as well. As a matter of fact, bandwidth allocation and call admission control (CAC) problems already arise in the integrated services digital network (ISDN) environment (see, e.g., [1-15] for this type of control problem in that context). The control strategies in this case are related to QoS at the call level, in terms of both cost or revenue functions and constraints (e.g., on call blocking probability).

The statistical multiplexing character of ATM adds another control level to this scenario, because it further requires the satisfaction of cell-level constraints. Except by peak bandwidth assignment to each virtual circuit (VC) connection, there is no immediately clear way to identify the amount of resources (buffer space and bandwidth) required by the connection during its lifetime. This has given rise to many investigations on the bandwidth allocation problem (and the related CAC strategies; see [16-29], among others). A number of works deal, in this respect, with the notion of equivalent bandwidth [20-28]; this binds the cell-level QoS guarantees and the statistical characteristics of a source with a bandwidth requirement (within known limits), thus allowing a separation between the cell- and call-level control problems.

Among the various approaches, some impose a certain structuring on the allocation of the resources, where typically services are subdivided into classes, which are homogeneous in terms of performance requirements and/or statistical characteristics of the traffic sources, and bandwidth is allocated accordingly, thereby restricting the statistical multiplexing only within each class; this does not sensibly degrade performance in the case of services with largely different QoS or statistical natures ([1, p. 141 and references therein]; see also [30, 31] for analyses of the multiplexing gains). This approach (service separation) has been adopted in various forms in a number of works in the literature ([1, 32-41], among others). This further eases the decomposition of a very complex overall control task, which is in general characterized by very different time scales and requirements, according to the level where the system dynamics is considered (e.g., cell and call level), into smaller and somehow independent problems. For instance, an essential decoupling between cell and call level is achieved in [34, 35] through the concept of Schedulable Region, whereas a hierarchical decomposition has been used by the authors in previous works [39, 40].

By adopting this philosophy, we distinguish and compare some bandwidth allocation and related CAC strategies at an ATM multiplexer serving a link with a given total transfer capacity, which essentially differ in the way the link bandwidth is allocated among the service classes (and, accordingly, the CAC operation is performed). All the strategies we describe in this article can be interpreted as defining partitions of the region in call space within which QoS constraints at the cell level are satisfied (referred to as the “feasibility region,” FR, in the following). Moreover, they belong to the family of complete partitioning strategies [1], where the bandwidth of the link is entirely divided among the classes in a static way. However, in our approach we shall see that quasi-static partitions may be obtained by successive adjustments based on traffic measurements.

Although the focus will be on the above-mentioned partitioning schemes, we will also need an algorithm to ensure the satisfaction of QoS requirements at the cell level within each
service class; typically, satisfying these requirements imposes a limitation on the number of acceptable connections for each class, which in turn determines the boundary of the FR. In all our methods but one there is no interaction between this cell-level control and the partitioning and CAC level above it. In general, any methodology (in particular, any based on equivalent bandwidth) could be applied; we will briefly describe the one introduced in [39, 40], which will also be used to obtain most numerical results. It takes into account constraints on cell loss probability and cell delay, and it yields the maximum number of connections that each class can support (i.e., the points on the boundary of the FR).

The article is organized as follows. The next section is devoted to a brief discussion of service separation and related bandwidth allocation and admission control schemes, as well as to the cell-level methodology for evaluating the FR. Four different quasi-static complete partitioning schemes are described in the third section, and their performance is investigated by simulation in the fourth section. The final section contains the conclusions.

**CELL- AND CALL-LEVEL CONTROL PROBLEMS UNDER SERVICE SEPARATION**

We suppose the traffic in the network to be divided into \( H \) classes of bursty (on-off) sources, each class being characterized by statistical parameters like peak rate, average transmission rate, and average burst length, as well as by QoS requirements like cell loss probability and cell delay. We indicate with \( B(h) \) (cells), \( P(h) \) (cells/s), \( M(h) \) (cells) and \( \beta(h) \) the average burst length, peak bit rate, average bit rate, and burstiness, respectively, of a source of the \( h \)th class. Moreover, let \( \lambda(h) \) and \( 1/\mu(h) \) represent the average arrival rate and average duration of connections of class \( h \), respectively, and \( P(h) = \lambda(h)/\mu(h) \).

At each ATM multiplexer, traffic class \( h \) is assigned a separate buffer of length \( Q(h) \) (cells), whose output is statistically multiplexed on the outgoing link by a scheduler, which substantially divides the global channel capacity \( C \) (cells) into "virtual" partitions \( C(h) \) among the classes, whose sum amounts to \( C \). The simplest way to maintain the partitions is by serving the buffer in a weighted round-robin fashion; other possibilities include the assignment of a slot (time to transmit a cell) to a cell of class \( h \) randomly, with probability \( \Omega(h) = C(h)/C \) [39], or the use of a technique such as generalized processor sharing [42].

Connection requests, which can come from the users directly connected to the node or from other nodes, are also processed on a per-class basis. Given a model for the traffic sources of a class, the cell-level performance requirements (e.g., in terms of average cell loss and delayed cell rate) allow a region to be defined in call space (which, as we mentioned in the introduction, is the FR), where they are certainly satisfied. This region corresponds to the CAC method named "service separation with dynamic partitions" in [1, p. 147]. In a network, one such region can be associated with each link.

Clearly, the points on the boundary of the FR correspond to the maximum numbers of VC connections \( N_{\text{max}}(h) \) that are compatible with the given cell-level QoS constraints. We can associate each \( N_{\text{max}}(h) \) with the minimum amount of bandwidth \( C_{\text{min}}(h) \), that is necessary to support that number of connections with the given QoS guarantees.

The computation of the FR has been the object of several studies and can be effected in different ways, either by analysis, given a model of the traffic sources, or by simulation. A more general view includes the characteristics and the optimization of the scheduling process [34], through the related concept of "schedulable region." Using any approach based on equivalent bandwidth (involving, in our service separation context, only homogeneous sources) yields a straightforward boundary of the FR. In any case, it is worth noting that, in the context of the methods to be considered in the next section, the FR itself will just be a tool to describe the CAC schemes. The specific technique to ensure QoS satisfaction at the cell level might be changed (always within the framework of service separation) without affecting the general access control procedure.

However, to fix ideas for the computations of the FR we refer here to the model we have used in [40] and in previous works, where a maximum threshold value is set for the average cell loss rate \( P_{\text{loss}}(h) \) and for the average delayed cell rate \( P_{\text{delay}}(n, C(h)) \), with \( n \) calls in the active state out of \( N(h) \) accepted calls and a bandwidth \( C(h) \) assigned to traffic class \( h \); more specifically,

\[
\sum_{n=1}^{N(h)} P_{\text{loss}}(n, C(h)) W_{n, N(h)} \leq \varepsilon(h) \tag{1}
\]

\[
\sum_{n=1}^{N(h)} P_{\text{delay}}(n, C(h)) W_{n, N(h)} \leq \delta(h) \tag{2}
\]

where \( \varepsilon(h) \) is an upper limit on the average value of the cell loss rate, and \( \delta(h) \) has the same meaning for the average value of cells that suffer a delay longer than a fixed upper bound \( D(h) \) in the fourth section. The quantity \( V_{n, N(h)} \) is the probability of having \( n \) active connections of class \( h \), with \( N(h) \) accepted connections of the same class, which is given by a binomial distribution; an interrupted Bernoulli process (IBP) [43] is used to model the state of a call, from which \( P_{\text{loss}}(n, C(h)) \) and \( P_{\text{delay}}(n, C(h)) \) are derived. \( N(h) \) and \( C(h) \) are computed from Eqs. 1 and 2.

As an example, the two FRs derived from the above method and from the equivalent bandwidth approach of [22] (labeled FR1 and FR2, respectively), are represented in Fig. 1 for two traffic classes whose parameter values are given in the fourth section. We stress again that a comparison between the two computation methods is not relevant in our context. Actually, in the particular case of our numerical values, there is a certain advantage in using the equivalent bandwidth approach, whereas other parameter combinations would enhance the previous method; it should also be kept in mind that the two approaches are not completely homogeneous, owing to the presence of constraint Eq. 2.

We let

\[
N_A(h)(k) = \text{col}[N_A^{(h)}(k), h = 1, \ldots, H]
\]

where \( N_A^{(h)}(k) \) is the number of connections in progress at the generic instant (slot) \( k \) for class \( h \). The vector in Eq. 3 repre-
sents the state of the system at instant $k$ (the VC-profile in [1]).

At this point, we are ready to consider QoS performance measures and constraints at the call level, having essentially decoupled this problem from the lower-level one. Obviously, a possible way of performing the CAC operation is that of accepting an incoming call as long as the VC-profile is within the FR. This, however, does not allow us to take into account periodic and asynchronous reallocation instances; in any case, the duration of the interval $t_{k+1} - t_k$ will typically be several orders of magnitude larger than the slot. For the time being, we only note that, whenever a reallocation is performed online, when the system is in operation, there is a set of “dynamic” constraints that must be taken into account. More specifically, in order to ensure the correct service continuation of all the connections already in progress at time $t_k$ we must have

$$N_{\text{max}}(t_k + \Delta) \geq N_A(t_k), \quad h = 1, \ldots, H$$

in the call space or

$$C(t_k + \Delta) \geq C_B(t_k), \quad h = 1, \ldots, H$$

in the capacity space; here, $C_B(t_k)$ is the lower bound on the capacity needed to ensure the QoS for the $N_{\text{max}}(t_k)$ class $h$ calls in progress at instant $t_k$ and we have obviously considered the all previously defined quantities as time-dependent. The effect of these constraints is the reduction of the set of values of $N_{\text{max}}$ to be considered in the optimization to a sub-set $N_{\text{opt}}(t_k)$ of the boundary $B_{\text{FR}}$ of the feasibility region, as shown in Fig. 2 (where the time indices have been dropped for simplicity). Correspondingly, only a subset $N_{\text{opt}}(t_k)$ of the feasibility region need be considered.

Having observed this, we can now turn to the definition of the optimization criteria to be used. In the first three methods we describe next, named the Erlang scheme (ES), the balanced Erlang scheme (BES), and the constrained Erlang scheme (CES), we suppose that the interarrival times of the call requests and the duration of connections of class $h$ follow exponential distributions, with average values $1/\lambda^{(h)}$ and $1/\mu^{(h)}$, respectively. Thus, in these cases, as a consequence of the usage of the service separation and the CP policy, we can easily compute, independently for each class $h$, the stationary blocking probabilities $P_B^{(h)}(N_{\text{max}})$, $h = 1, \ldots, H$ by using the Erlang B formula [1]. By supposing a slow variation of the rates $\lambda^{(h)}$, $\mu^{(h)}$ with respect to the call request dynamics and reallocation interval, we utilize an infinite horizon cost formulation (i.e., averaging according to stationary distributions) and define three different cost functions, based on the quantities $P_B^{(h)}(N_{\text{max}})$, $h = 1, \ldots, H$.

In the ES, the maximum numbers of acceptable calls $N_{\text{opt}}$ are computed through the minimization of a weighted sum of the per-class blocking probabilities, namely

$$N_{\text{opt}} = \text{arg} \min_{N_{\text{max}}} \left\{ \sum_{h=1}^{H} \alpha^{(h)} P_B^{(h)}(N_{\text{max}}) \right\}$$

where

$$P_B(N_{\text{max}}) = \sum_{h=1}^{H} \alpha^{(h)} P_B^{(h)}(N_{\text{max}})$$

and the $\alpha^{(h)}$ are weighting coefficients. If

$$\alpha^{(h)} = \frac{\lambda^{(h)}}{\sum_{k=1}^{H} \lambda^{(k)}},$$

Eq. 7 represents the average blocking probability of the multi-
plexer. Clearly, in this case, the main goal is to minimize the total blocking probability of the system, giving also the capability to assign a sort of priority to some traffic classes through the weights $\alpha^{(h)}$, $h = 1, \ldots, H$.

On the other hand, in the BES the main goal is the achievement of an equalization of the blocking probabilities over the classes, and this result is obtained by using the following cost function:

$$P_B(N_{\text{max}}) = \max_h \left\{ \alpha^{(h)} P_B^{(h)}(N_{\text{max}}) \right\}$$

so that

$$N_{\text{max}}^{\text{opt}} = \arg \min_{N_{\text{max}} \in S_3} P_B(N_{\text{max}})$$

Again, the weights $\alpha^{(h)}$ offer the opportunity to change the relative "importance" of each class.

The third scheme we present is defined by adding a (stationary) constraint on the maximum call blocking probability for each class; that is,

$$P_B^{(h)}(N_{\text{max}}) \leq \gamma^{(h)}, h = 1, \ldots, H$$

Let $\bar{N} = \text{col}(N^{(h)}, h = 1, \ldots, H)$ be the equality solution of Eq. 10 with respect to $N_{\text{max}}^{\text{opt}}$. To satisfy the constraints in Eq. 10 we must then have

$$N_{\text{max}}^{(h)} \geq \bar{N}^{(h)}, h = 1, \ldots, H$$

We can distinguish two cases: $\bar{N} \in S_R$ and $\bar{N} \notin S_R$. In the first, a subregion that satisfies the constraints (shaped as shown in Fig. 3a for a system supporting two classes) can be found; in the other case, the subregion does not exist (Fig. 3b). On the basis of these considerations, we compute $N_{\text{max}}^{\text{opt}}$ as the vector minimizing the blocking probability $P_B(\bar{N}_{\text{max}})$ in Eq. 7 within the subregion of $S_R$, where the constraints of Eq. 10 are satisfied if $\bar{N} \in S_R$; otherwise, we try to approximate the constraints as closely as possible by choosing $N_{\text{max}}$ so as to minimize the sum (over the classes) of quadratic deviations between the blocking probability of each class and the corresponding constraint value. In other words, we may interpret this operation as looking for the $N_{\text{max}}$ at minimum "distance" (in the above sense) from $\bar{N}$ (Fig. 3b).

At this point, we can specify how the reallocation is performed in conjunction with the three methods above. In this case, the parameters $k^{(h)}$ and $\mu^{(h)}$ of the connections can be continuously estimated and, whenever a significant change is observed, the reallocation can be called upon to compute new values of $N_{\text{max}}^{\text{opt}}$ and corresponding bandwidth partitions. Thus, the overall scheme can be viewed as a parameter adaptive certainty equivalent control [44], and the reallocation is normally effected at asynchronous instants.

Our fourth method, which will be referred to as DRS (dynamic reallocation scheme) in the following, differs from the above-described ones in some respects. First of all, no assumption is made on the statistical nature of the call arrivals and durations; this fact does not allow defining any cost function averaged over a stationary probability distribution of the call process. We therefore change our view of the cost function, and also the general organization of the control architecture. The reallocation is made periodic, and the bandwidth partitions can be interpreted as coordination variables in a two-level hierarchical scheme with repetitive control [39, 40] (the "lower" level consists of the per-class admission control).

In this respect, the cost function to be used in the bandwidth allocation process is now based on the same quantities that have been introduced in the previous section in conjunction with the cell-level control problem. More specifically, it involves an estimate of the overall cell loss rate that would be generated by the total offered load, measured over the previous interval. The basis for this computation is given by the expression on the left side of Eq. 1. However, a linear combination of two different sums is constructed:

- One extending up to the average number of connections in the system over the previous interval
- Another extending over the total number of connection requests (either accepted or rejected), still averaged over the previous interval

The aim is to obtain a quantity that reflects the variation in cell loss rate which would have been incurred by accepting all incoming calls and, in turn, to allow detection of changes in the load proportions among the classes. The detailed expression of the cost function is not reported here (see [39, 40]).

The length of the reallocation period can be chosen as a compromise between two requirements: that the interval be long enough to contain a reasonable number of sample points (of the call arrival process) with a given probability, but not "too long," in order to allow a fast reaction to sudden load variations. In any case, its length will typically be comparable to the call time scale, which is some orders of magnitude larger than the cell scale.

Two facts are worth noting that are common to all the methods we have described: i) the reallocation operation gives rise to different complete partitioning "rectangular" regions, with a vertex moving on the boundary of the FR to adapt to load variations (see Fig. 4); and ii) the admission control rule for each class $h$ is very simple, involving only a comparison of the current number of connections plus the new one with the current value of $N_{\text{max}}^{(h)}$; new values of these quantities have to be computed only at the beginning of a reallocation period or epoch. From the point of view of implementation, this computation is the heaviest one, and would deserve careful investigation.
In all schemes considered, it requires performing a number of descending steps of a mathematical programming method for the parametric minimization of the specific cost function. In this respect, the DRS cost function evaluation is relatively more complex than those of the other methods. Nevertheless, it has already been noted that the length of the reallocation periods should at least be comparable to the average time between successive events in the call processes, or even span several such time intervals in most cases; moreover, call requests coming in during the computation may be temporarily held until its completion, and several other possibilities exist, along similar lines to [1S, App. C], to improve the feasibility of this procedure.

**Simulation Results**

The first part of this section is aimed at showing the differences among the various strategies introduced previously. The schemes are tested with two service classes, over a range of the traffic loads $p(i)$, $i = 1, 2$. The overall channel capacity is $C = 150$ Mb/s.

We normalize the traffic flow to that generated with the data specified in Table 1, when $p(1) = 200$, $p(2) = 30$; we refer to this load as unity. An offered load "x" corresponds to the same data, except for the traffic intensities, which are multiplied by $x$. The bandwidth reallocation for the DRS is performed at fixed instants $(t_k)$, every 905.6 s (about 1.5 minutes). A simulation run for each constant traffic load value lasts 48 of these reallocation intervals (obviously, in this case, the reallocations are performed only for the DRS). So, the duration of the overall simulation is 43,468.8 s (i.e., about 12 hr network time). This duration guarantees a high level of reliability of the measured values; more specifically, the results have a 95 percent confidence interval around 3 percent of the estimated value, or less.

Figures 5–9 are dedicated to this first part. The second part of the results has a different aim. Specifically, the object is to simulate time-varying traffic conditions, as may happen in a real situation; therefore, the traffic load is changed during the simulation every 8 reallocation intervals (2 hr network time), as it might do in a real network depending on the time of day. The goal is to get some indications on the response time of each mechanism. In this context, the bandwidth assigned at each reallocation is also shown. As in the previous case, the duration of each simulation corresponds to about 12 hr network time. This division of time is well suited, in this case, to approximating the behavior during a day. Figures 10–14 are related to this second part. The data used for both parts are the same (except for the traffic loads) and are summarized in Table 1.

Figure 5 shows the global percentage of blocked connections for the strategies DRS, ES, BES, and FRS. The last acronym stands for "feasibility region scheme," which is a simple strategy where a connection is accepted whenever the system's state remains within the FR after acceptance. It is presented here just to allow a further comparison among the methods. FR1, stemming from Eqs. 1 and 2, has been used. As can be seen from the figure, the ES provides the best results, and the overall percentage of blocked connections is relatively small even at high load. On the other hand, the worst result is obtained by using the BES scheme, whose aim is not the minimization of the global percentage of blocked calls, but rather balancing the blocking probability between the classes. The results concerning the CES mechanism are not reported.

**Table 1. Parameter values.**

<table>
<thead>
<tr>
<th>Traffic class: $h$</th>
<th>$h = 1$</th>
<th>$h = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak bandwidth: $p_i$</td>
<td>2 Mb/s</td>
<td>10 Mb/s</td>
</tr>
<tr>
<td>Burstiness: $b_i$</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Average burst length: $b_i$</td>
<td>500 cells</td>
<td>1000 cells</td>
</tr>
<tr>
<td>Average connection duration</td>
<td>15 s</td>
<td>25 s</td>
</tr>
<tr>
<td>$P_{\text{delay}}$ upper bound: $e_i$</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>$P_{\text{delay}}$ upper bound: $g_i$</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Delay constraint: $D_i$</td>
<td>200 slots</td>
<td>1000 slots</td>
</tr>
<tr>
<td>Buffer length: $Q_i$</td>
<td>15 cells</td>
<td>10 cells</td>
</tr>
</tbody>
</table>
in this figure, as they would not be meaningful in this form, due to the fact that the constraints are referred to each traffic class and not to the overall percentage.

To see the effect of a change in the shape of the FR on the CAC strategies, the graphs referring to ES, BES, and FRS are represented again in Fig. 6, this time by using FR2 produced by equivalent bandwidth. The DRS is not reported in this case, since its call-level cost is anyway intimately connected with Eqs. 1 and 2, as noted in the previous section. It can be seen from this figure and the preceding one that the shape of the FR (depending on the accuracy of the specific computation method and of the source models) obviously affects the performance of the CAC strategies. However, two facts are worth noting:

- The qualitative behavior with increasing load is the same.
- As far as CP strategies are concerned, this effect is limited to the point of the boundary where the vertex of the "rectangle" is positioned.

Actually, the BES, whose vertex sticks to the right of the FR (where FR2 has the advantage, as can be seen from Fig. 1) at high load, exhibits a gain in Fig. 6 over Fig. 5; on the other hand, the ES, which is placed almost at the crosspoint of the two boundaries in Fig. 1, maintains an almost equal call-level performance.

The small number of blocked calls for the ES scheme is "paid" for by a strong unbalance between the traffic classes. This can be seen in Fig. 7, where the percentage of blocked connections is shown for the same strategies as in Fig. 5, but where the values referred to each traffic class are presented. The BES strategy provides really balanced results, as was the aim of this scheme. The same comments as above can be made regarding Fig. 8, where the same situation is reported with respect to FR2 (except the DRS).

Having established the comparison with respect to the choice of FR, to fix ideas from now on we will refer to the specific choice of FR1 and concentrate on the different behavior of the various CAC and bandwidth allocation methods we have introduced. The same quantities as in Fig. 7 are reported in Fig. 9 for various configurations of the CES scheme. Some explanation of the notation is necessary: CES \( (x\% - y\%) \) means that the upper bounds for the percentage of blocked connections are \( x \) (concerning class 1) and \( y \) (concerning class 2), respectively. Referring to the theory in the previous section, this means that \( \gamma^{(1)} = 0.01 \cdot x \) and \( \gamma^{(2)} = 0.01 \cdot y \) (recall that \( \gamma^{(h)} \) is the limit on the call blocking probability of class \( h \)).

It can be seen that, concerning CES \( (20% - 20\%) \), the constraints are respected as far as possible (load 0.4 and 0.5); then the strategy tends to maintain the losses of the two classes near the constraint value: the final effect is an actual balance between the two classes. Concerning the other configurations, the constraints are basically respected. In order to appreciate this property even at very high load, one of the traffic classes has been given a very "loose" constraint (90 percent); in this case, some room is always left to satisfy the more stringent constraint of the other.

We now turn to the second part of results, under the time-varying load configuration, which is shown in Fig. 10. The load of class 2 remains constant for the entire duration of the simulation, whereas the load of class 1 varies every 8 reallocation instants (2 hr). For homogeneity and better comparison, the adaptive schemes (ES, BES, CES) are also updated regularly at each reallocation interval of the DRS.

Figures 11 and 12 are aimed at showing the reaction of the system to traffic variations. Figure 11 shows...
the values of the maximum number of acceptable connections for each traffic class at each reallocation instant (for DRS, ES, and BES). Clearly, the values are different for every strategy, but the response of the system to a load step variation is noticeable. The same behavior can be found in Fig. 12, where the bandwidth allocated to each class at each reallocation instant is shown for the same strategies. A similar behavior can be obtained for the CES scheme.

The last figure (Fig. 13) shows the average percentage of blocked calls under the time-varying load configuration for both the single classes and the overall number. As in Fig. 5, even in this case the aim is to show the different behavior of each strategy. Because the traffic conditions are so varying, the global behavior is different than in Fig. 5, but the same general considerations can be made. The balancing effect of BES, DRS, and CES (20% - 20%) is noticeable, as well as the low total number of blocked connections and the large unbalance of ES. The CES strategy is really effective (CES (90% - 10%) and (90% - 1%), in Fig. 13), if the attainment of a precise bound on the call blocking probability of each class is allowed, even at very high load; both stringent requirements (10% and 1%) are, in fact, respected.

CONCLUSIONS

We have examined and compared different bandwidth allocation and call admission control strategies for ATM networks. Our approach has been in the context of service separation, where traffic sources have been grouped into classes, homogeneous in terms of performance requirements and statistical characteristics. Given the cell-level constraints for each class (namely, upper bounds on cell loss and delay probabilities or rates), a region in the space of connections ("call space") of each class can be easily defined, where a point represents a combination of the numbers of connections of each class that satisfy the constraints. Within this "feasibility region" (FR), we have considered different bandwidth allocation (and the corresponding CAC) schemes, all belonging to the family of complete partitioning strategies, which define a "rectangular" subregion with a vertex on the boundary of the FR.

All schemes have been embedded within an overall adaptive control architecture, whereby their parameters are recomputed, either periodically or at asynchronous instants, at a rate comparable with the time scale of the connection requests. The computational complexity of the overall procedure has been briefly discussed. The different performance characteristics have been compared by simulation, in both cases of static and time-varying traffic parameters. The results show very satisfactory behaviors in accordance with the intended goals.

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REFERENCES


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