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SIMULATIVE ANALYSIS OF ROUTING AND LINK ALLOCATION STRATEGIES IN ATM NETWORKS

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Abstract

For Broadband Integrated Services Digital (B-ISDN) networks ATM is a promising technology, because it supports a wide range of services with different bandwidth demands, traffic characteristics and QoS requirements. This diversity of services makes traffic control in these networks much more complicated than in existing circuit or packet switched networks. Traffic control procedures include both actions necessary for setting up virtual connections (VC), such as bandwidth assignment, call admission, routing and resource allocation and congestion control measures necessary to maintain throughput in overload situations.

This paper deals with routing and link allocation, and analyses the performance of such algorithms in terms of call blocking probability, link capacity utilization and QoS parameters. In our model the network carries out the following steps when a call is offered to the network:

(1) Assign an appropriate bandwidth to an offered call (Bandwidth assignment)
(2) Find a transmission path between the source and destination with enough available transmission capacity (Routing)
(3) Allocate resource along that path (Link allocation)

We consider an example 5-node network [7], conduct an extensive survey of routing, and link allocation algorithms. Regarding step (1) we employ the equivalent link capacity assignment presented by various interesting papers [1]–[5]. We find that the choice of routing and link allocation algorithms has a great impact on network performance, and that different routing algorithms perform best under different network load values. Shortest path routing (SPR) is a good candidate for low, alternate routing (AR) for medium and non-alternate routing (NAR) for high traffic load values.

Concerning link allocation strategies, we find that partial overlap (POL) strategies that seem to be able to present near optimal performance are superior to complete sharing (CS) and complete partitioning (CP) strategies. As a further improvement of the POL scheme, we propose a 2-level link allocation algorithm, which yields highest link utilization. In this scheme, not only the accesses of different service classes to different virtual paths (VPs) are controlled, but also an individual VP's transmission capacity is optimally allocated to the service classes according to their bandwidth requirements in order to assure high link utilization. This method seems to be adjustable to the fine degree of granularity of bandwidth demands in B-ISDN networks.

It is shown that in order to minimize cell loss the call level resource allocation plays a significant role: networks with the same buffer size switches display different cell loss probabilities in the nodes and impose different end-to-end delay on cells if the link allocation and routing differ. Again, we find that when traffic is tolerable by the network, SPR causes the least cell loss. This can be explained by the fact that SPR spreads the incoming calls in the network. It eagerly seeks new routes instead of utilizing the already used but still not congested routes. SPR obviously wastes more rapidly link and buffer capacity as traffic load becomes higher than the AR, which chooses a new route only when it has to, i.e. when the route of higher priority becomes congested. That is why we experience that as soon as the SPR starts loosing cells, it indicates that available resources have been consumed and it rapidly goes up to very high blocking probabilities after a small further increase of load.

Keywords: Asynchronous Transfer Mode, Broadband Integrated Services Digital Networks, routing, resource management, multirate circuit switched networks.

1. Introduction

Asynchronous Transfer Mode (ATM) is the only switching and multiplexing technology available today that is able to support a wide range of services in the local, metropolitan and wide area networks with quality of service (QoS) guarantee. This broad spectrum of services (including LAN-LAN communications, voice and video communications and image retrieval services [8]) has drastically different traffic characteristics, such as peak/mean rate, burst length and QoS requirements, such as tolerable cell loss probability, cell delay and cell delay variation.

Access nodes have to exercise traffic control procedures in order to fairly allocate switching and transmission resources to the various service types and mixes carried by the network. Part of the traffic control is the bandwidth assignment activated at the call set-up phase. At this point the network has to assign an appropriate bandwidth to the new call on the basis of its statistical characteristics and taking into account the calls already in progress such that in case the new call is accepted both the already ongoing calls and the new call operate at a satisfactory level in terms of cell loss and cell delay. In the near past a number of interesting papers [1]–[6], [9]–[10] were devoted to the problem of finding an equivalent capacity that takes into account the aforementioned call parameters and results in efficient network resource utilization by allowing the network to allocate less capacity to the call than its peak rate.

Once an appropriate equivalent bandwidth has been calculated, the network has to decide whether to accept the new call, or not depending on the availability of routes in the network between the source and destination node, sufficient transmission resource (i.e. free bandwidth) and switching resource (i.e. buffers and translation tables in the switches) along that route. In ATM, a virtual channel (VC) connection has to be established between source and destination through virtual paths (VP). (In ATM a VC connection is always established inside VP links [11], [12]). Since we expect high reliability and availability from these networks, normally there should be a couple of such routes in the network and possibly different virtual paths along these routes. It is the task of the resource allocation strategy to select from the available transmission links and virtual paths through which the virtual channel connection should be established. This strategy not only affects the call blocking probability of successive calls, but also will impose different load to the switches and thus will result in varying QoS parameters of the accepted calls. Obviously, to formulate an optimal resource allocation algorithm is a complex task [1-4], [24].

This paper focuses on two interdependent tasks of resource allocation in B-ISDN networks: (1) at VC connection (call) set-up time to find a series of transmission links (route), which have sufficient bandwidth to support the call and (2) to select the appropriate VP links within these transmission links and allocate bandwidth within the VP links, through which the necessary VC connection will be established. We refer to the first step as routing and to the second as link allocation. In this paper, we assume that transmission links give room to several VP links and that the VP links are allocated on a semi-permanent basis before the VC connection set up time. Also in order to study the effect of routing and link allocation on call blocking, the network under study will have VP links that are allocated on a single physical link, that is, without loss of generality from the resource allocation point of view we exclude VP links that traverse through a concatenation of physical links. The refinement of the partial overlap link allocation scheme that we propose does not take advantage of this simplification, which is merely done for the sake of simplicity in this demonstrative example we present here.

It has been early recognized [1, 24] that traffic control at the call level may reduce blocking at the cell level (i.e. cell loss). However, the joint analysis of resource allocation strategies at these two levels is an extremely complicated task. Further, analytical studies exclusively dedicated to the performance characteristics of routing algorithms when operating on circuit switched networks are constrained either by the number of services or by the topology assumptions [14]–[16]. These models become quickly untractable as we combine the different routing algorithms with different link allocation schemes and wish to study the joint effect of these algorithms, so to evaluate call blocking, cell loss and cell delay between communicating end nodes when applying different routing and link allocation algorithms we resort to simulation. Specifically, we apply the method of conservative parallel discrete event simulation (PDES) to study the network behavior at the cell level partly to exploit the power of modern shared memory multiprocessor computers, partly to model the simultaneous operation of the ATM switches inside the B-ISDN network.

The rest of this paper is organized as follows. Section 2 presents the basic assumptions on traffic sources, service characterization and network architecture. Next, in Section 3 we give a quick operational description of the simulation software called Flexible Simulation Platform (FSP) [18], [23] we used throughout this simulation study. We present results on the impact of routing and link allocation on call blocking in Sections 4 and 5. Based on these results in Section 6 we propose a two-level link allocation rule to improve VP link utilization and reduce call blocking. The impact of routing on QoS parameters is studied in Section 7. Section 8 draws conclusions and outlines further research.

2. ATM Network Model and Input Parameters

The FSP for ATM networks [18], [23] has been developed in order to simulate routing and link allocation in networks with arbitrary topology, number of nodes, link sizes and permanent VP/VC arrangements at the call level. It employs the conventional discrete event simulation (DES) algorithm to simulate VC connection establishment and release events that manipulate the link capacities as state variables in the program according to the actual routing and link allocation algorithm under study. The information model of FSP was proposed by [18], which defines a finite set of object instances, where each object is associated with a well-defined portion of the ATM network, such as a VP/VC switch, a transmission link or a VP link. Containment relationships between objects in the ATM network (e.g. a transmission link may contain several VP links) are supported by the hierarchy of objects in which the FSP stores these objects. The FSP provides both a graphical and a text based user interface to allow the user to define network objects and topology. At the call level the FSP does not take into account the statistical behavior of the traffic sources (generation of ATM cells) in detail, the effect of statistical multiplexing in the cell level resource allocation [1] is not considered on the call level resource allocation. Thus the basic assumption regarding resource allocation at the call level is that Bi ($i = 1, 2, 3$ denoting the 3 service classes (*Fig. 1*) with the low, medium and high bandwidth demand) basic bandwidth units (BBUs, typically Mbit/s), representing the equivalent capacity of the bandwidth are enough to ensure an acceptable cell loss rate for traffic type i (i.e. at the call level we treat the network as a multirate circuit switched network [26]). It allows the performance analysis of different routing and link allocation algorithms. Excellent application and interesting simulation results using the FSP on multicast routing performance analysis can be found in [27].

In this paper we will consider traffic sources generating calls with exponential interarrival and holding time, even though the FSP does not restrict the traffic source model to any probability distribution function. Poisson models, however, are easy to interpret and allow us to compare analytical

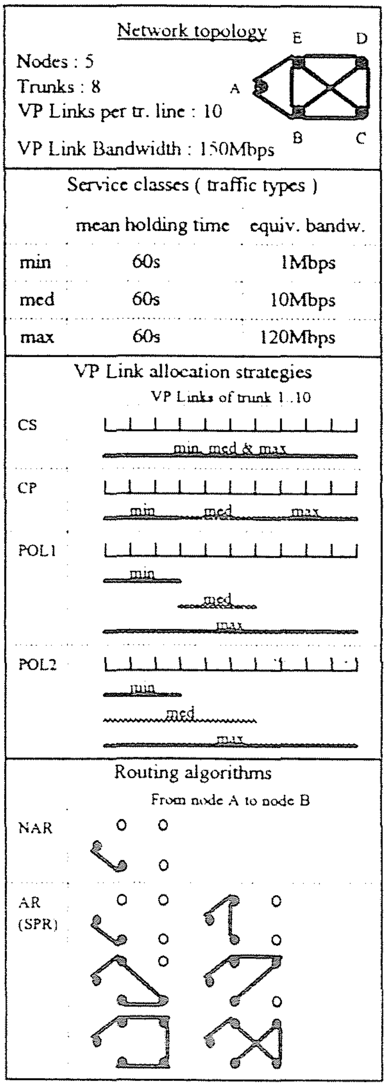


Fig. 1. The network under study

and simulation results to some extent. Thus, service classes are characterized by the call intensity, mean value of holding time and equivalent bandwidth demand. (The multiple of the former two quantities give the offered traffic in Erlangs, while the multiple of the three quantities give the offered load in Erlang $\times$ Mbit/s.) The FSP accepts any number of traffic sources belonging to the various service classes associated with the network nodes.

Call requests are served by non-alternate routing (NAR), shortest path routing (SPR) and the alternate routing (AR) algorithm. In the first a

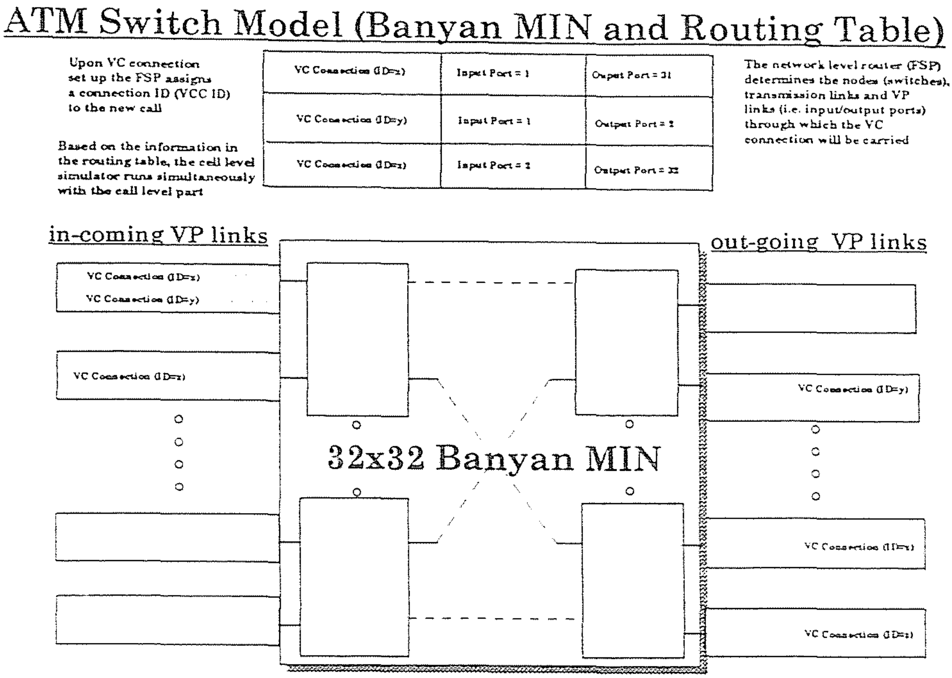


Fig. 2. ATM switch model

single predefined route is available between source and destination pairs, the second uses the well-known Dijkstra algorithm to find all available routes and uses a weight function (reciprocal value of free available bandwidth) to come up with the actual, and the third uses a table of candidate routes in a defined order and tries one after the other until one has sufficient bandwidth. A certain route can be used if there is at least one VP on each transmission link of that route that is able to provide bandwidth to the VC connection that will carry the offered call.

Once the route has been determined, the link allocation takes place, the actual VP link on each link is selected, and transmission capacity is reserved for the duration of the call. In complete sharing (CS) (*Fig. 1*), all service classes may choose any of the available VP links to reserve bandwidth. In contrast, in complete bpartitioning (CP), the VP links in each transmission link are numbered and assigned to specific service classes. In this scheme a virtual call may exclusively use the VP links assigned to the service class that belongs to to establish a call regardless of the availability of transmission capacity in other VP links. Partial overlap policies (POL) mix these two algorithms by defining both dedicated and shared VP links. (There are several algorithms according to which the actual VP link can be chosen out of the ones available in a transmission link, as noted in section 4).

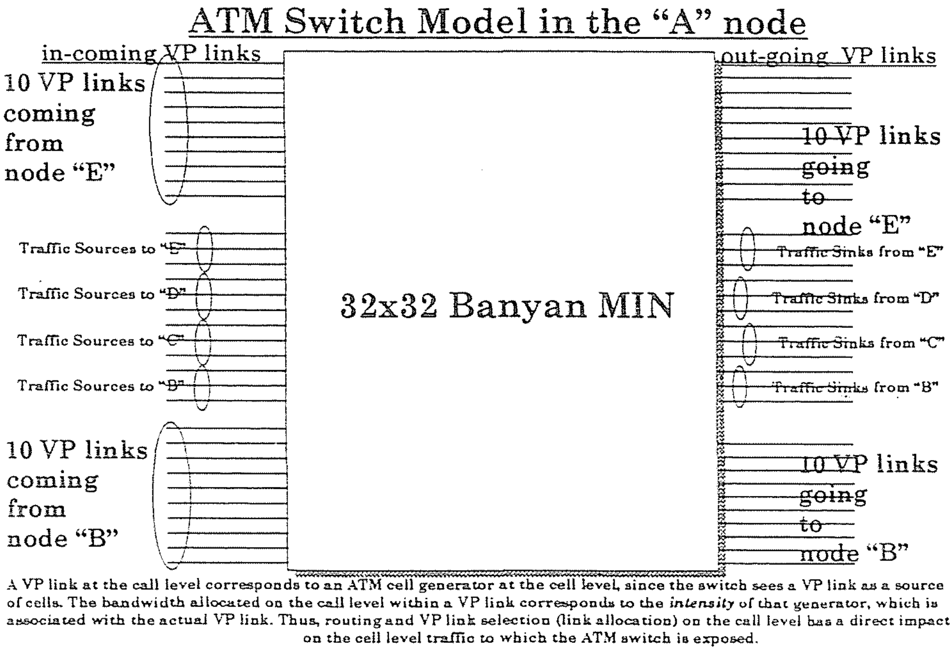
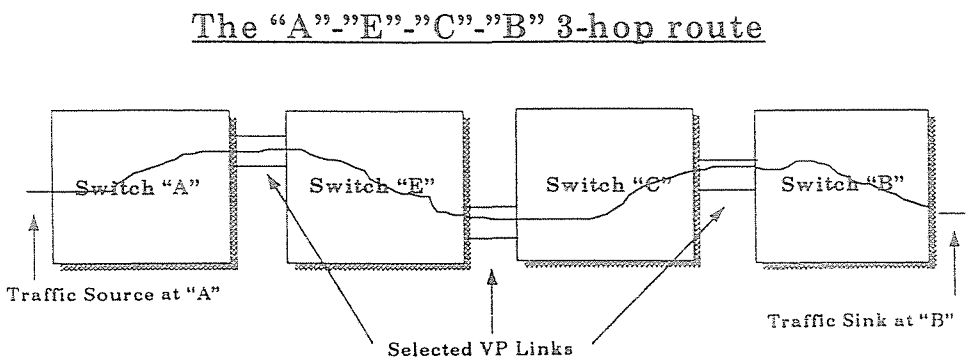


Fig. 3.a. ATM switch model in the 'A' node



1. The traffic source at node "A" initiates a call (VC connection request) according to the probability distribution function which characterizes this traffic source.
2. The FSP router finds the route "A"-"E"-"C"-"B" and the FSP link allocator selects VP links in each transmission link for the VC connection which will carry this call.
3. After route and VP link selection this information is placed into the routing tables of the actual switches.
4. The Cell Level Switch Simulators (one for each switch) adjusts the intensity of the generators connected to the switches corresponding to the selected VP links.
5. The traffic sink at node "B" analyzes incoming traffic (i.e. it counts the number of cells received and performs statistical analysis on cell delay)

Fig. 3.b. The 3-hop route under study

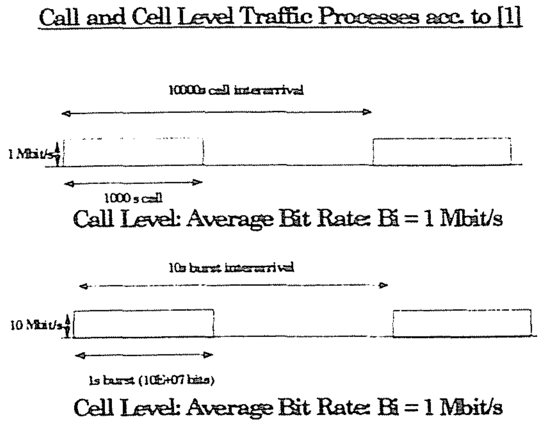


Fig. 4. Multilevel traffic process

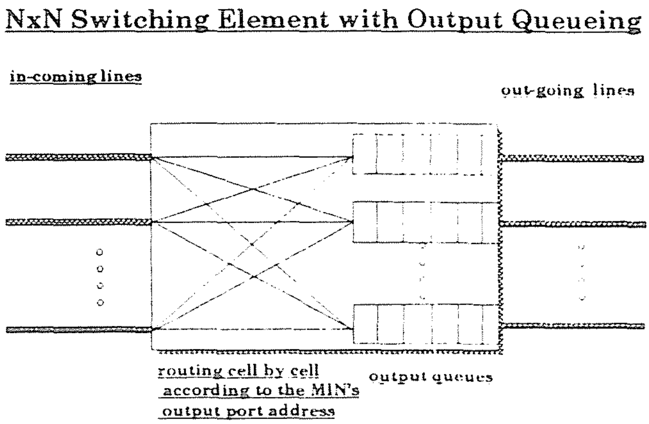


Fig. 5. $N \times N$ switching element

All three link allocation schemes are common in not specifying the capacity allocation within a VP link, i.e. the total capacity of shared VP links is available to the traffic classes which are at all allowed to use that link. (*Figs. 1* and *9*). As our simulation results show (see section 6) this policy tends to deprive bandwidth from the broadband traffic sources and unfairly favors narrow band services. Therefore, we introduce here the second level of link allocation, which takes place inside the individual VP link. This level has significance only for shared VP links, but as we will see, high network utilization can be reached only by highly shared links (i.e. if many service classes share the VP links).

The FSP supports gathering statistical information on demand while the simulation is running. Statistics may include route and link blocking, route usage (i.e. how many times a given route has been used by a specified

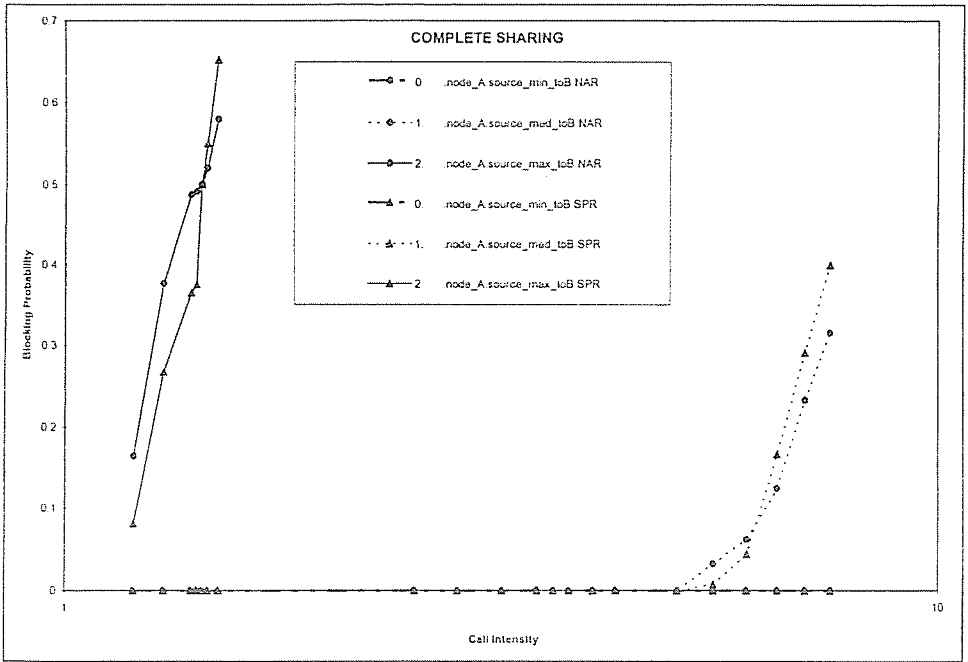


Fig. 6. Complete sharing

traffic source) and VP link usage (i.e. in average how big portion of the VP link capacity has been utilized). The input parameters (network topology, link capacities, service classes, traffic sources, routing and link allocation algorithms) are given in *Fig. 1*. We consider a 5-node network [7] (*Fig. 1*) with one transmission link between nodes of a capacity 1500 Mbit/s. This transmission link can e.g. be a trunk of optical fiber links with an aggregate bandwidth of 1500 Mbit/s. Each transmission link gives room to 10 VP links with equal capacity of 150 Mbit/s. Services $i = 1, 2$ and 3 are characterized by an offered traffic $Ai = \lambda_i/\mu_i$ in Erlangs. We choose the different bandwidth demands (Bi) in a way that the offered load defined as $Si = Ai \times Bi$ are equal. This is to assure meaningful comparison of virtual call blocking probabilities. The mean holding times are taken to be constant and equal to 60 TU's ($1/\mu_i = 60$ TU's). (In *Figs. 6–8* the X axis shows the intensity of the highest intensity class, i.e. service class 1.) A call generated in a node of the network is destined to all other nodes with equal probability.

Although simulation results on call blocking between each pair of nodes are available, we will select a node pair (say A-B) and present results concerning these two nodes. Other pairs confirm the results presented herein. Concerning the CP case, the obvious question is how to assign the dedicated links to the service classes (i.e. how big portion of the transmission link ca-

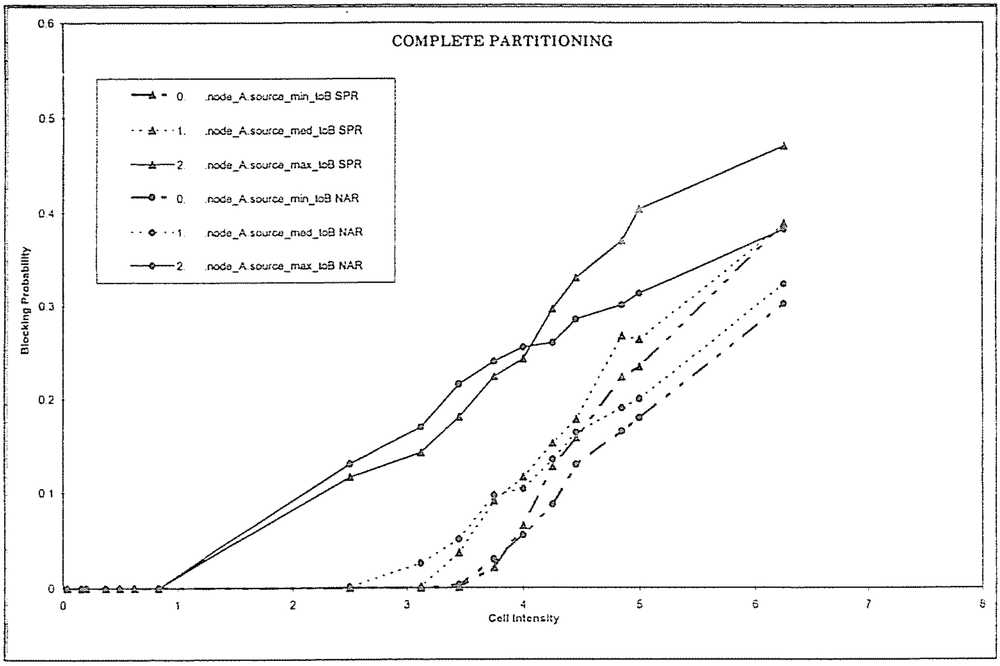


Fig. 7. Complete partitioning

pacity or in case of fixed VP link capacities how many such links should be given to the different service classes). In the POL case, an additional question is which of the VP links should be dedicated and which should be shared. Several efforts have been made to answer the former [12], [13], and a method combining these ones with the sequential hunting algorithm [7] will be proposed in Section 6 to answer the latter.

Link allocation and routing methods are selected independently of each other, and while studying the effects of the one, this will be changed, while the other will be kept constant.

3. ATM Switch Model and Interaction between the Call and Cell Levels

In this section we try to describe (1) the ATM switch model developed for conservative parallel discrete event simulation (PDES); (2) the way how events at the call level (i.e. VC establishment and release as described in Section 2) trigger events at the cell level (i.e. ATM cell arrival and departure) and (3) relevant implementation details of the multistage interconnection network (MIN) part of the switch.

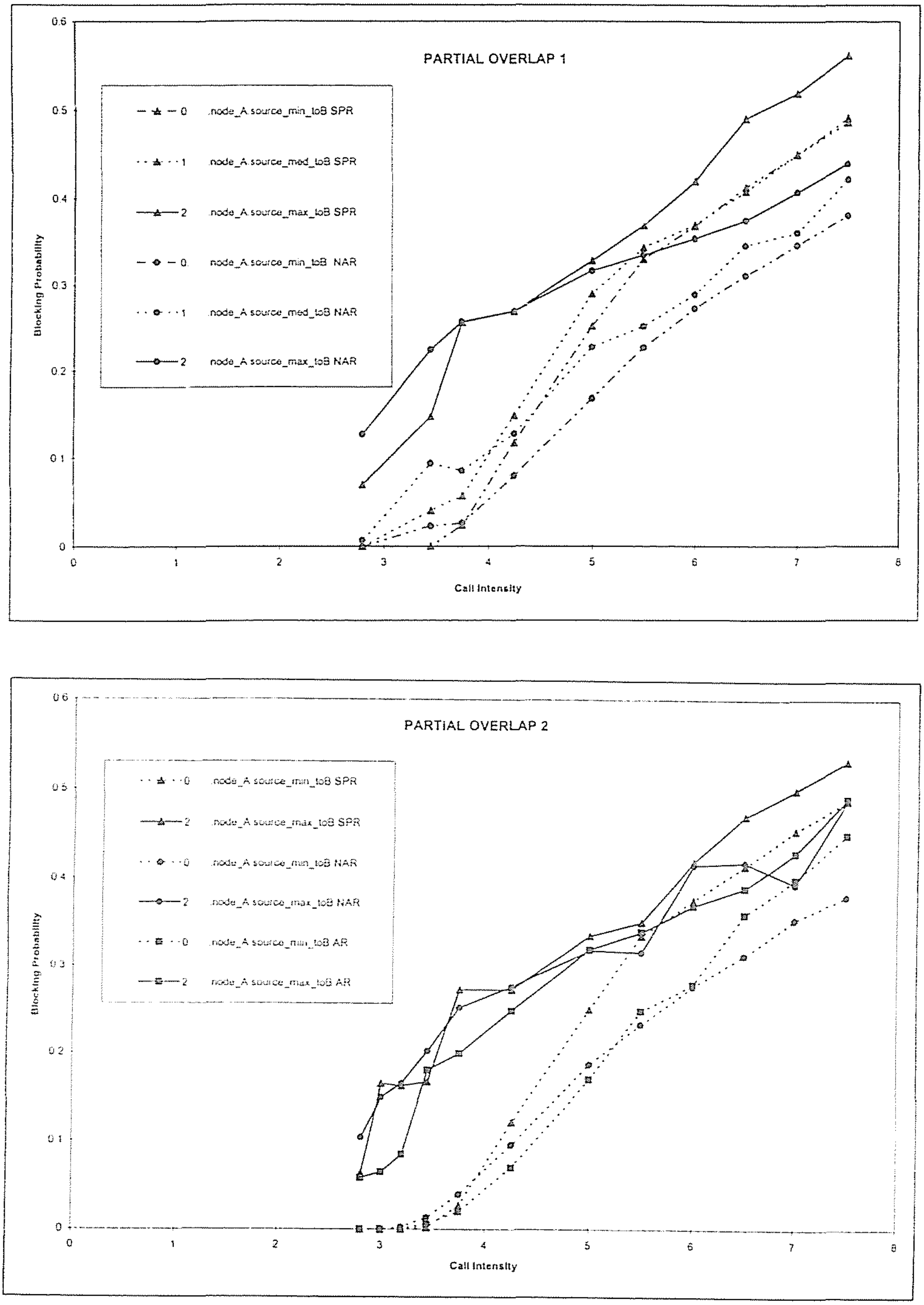


Fig. 8. a) Partial overlap 1 b) Partial overlap 2

In order to be able to study the effect of statistical multiplexing and statistical behavior of the traffic sources (generation of ATM cells) a simple model of the ATM switch has been developed in the parallel programming language uC^{++} [28], [29], and has been put into the nodes of the network. The switch model consists of a routing table and a switching fabric implemented as a MIN composed by several stages of switching elements. The uC^{++} code allows the use of any size of switching elements, the results discussed here, however, apply to MINs consisting of 2×2 switching elements (*Fig. 2*). The routing table is used to communicate routing information from the call level to the cell level, i.e. upon VC connection set-up the network level router places information into the actual switches routing table specifying the incoming/outgoing VP links connected to the switches along the route. This information then will determine which input/output ports will be used in the MIN for the cells belonging to this VC connection.

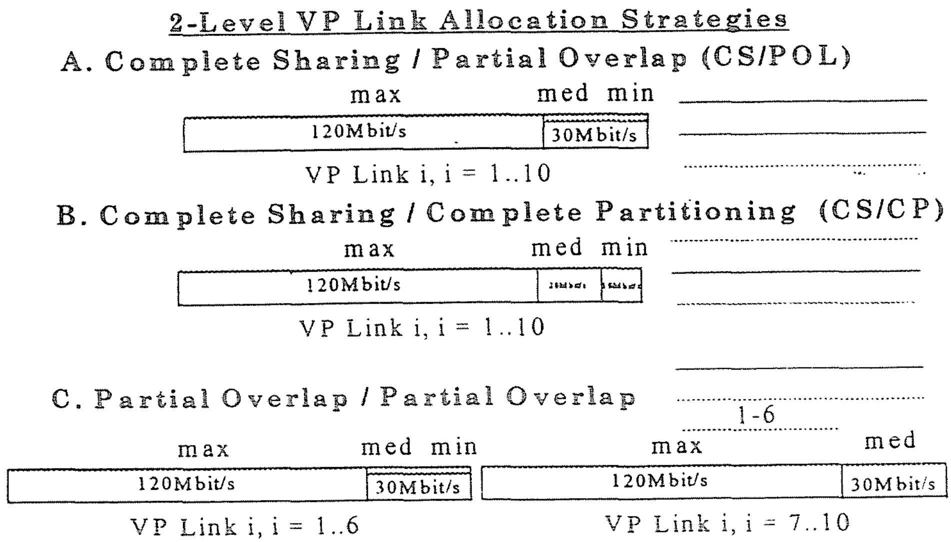


Fig. 9. 2-level VP link allocation schemes

The MIN is a Banyan network, the major property of which is that there exists exactly one path from any input to any output [11], [12]. Different subclasses of Banyan networks have been defined, the Delta and Omega networks are the most famous of them. The Delta and Omega networks have the self-routing property, i.e. independent of the input port at which the ATM cell enters the MIN, it will always arrive at the correct output port. The route to be followed inside the fabric can be described by a single string of digits called the routing tag, which is the binary address of the output port. The major characteristics of the these networks are [11]:

(1) they are constructed of identical $b \times b$ switching elements

(2) their regularity and interconnection pattern make them very suitable for very large scale chip integration (and for parallel simulation)
(3) they have the self routing property, requiring $\log_b N$ digits to route a cell from any input to any output
(4) they consist of $\log_b N$ stages, each having N/b basic switching elements

These MINs are internally blocking, since it may happen that cells (destined to different output ports of MIN) internally contend with each other for the same resource (i.e. link or output port), and thus they may get lost if no special provisions are taken [11]. There are several ways to reduce the internal blocking to a level which is acceptable for the given application; in our model we place queues (buffers) at every output in each switching element to provide for temporary storing of competing cells.

With respect to routing decision time inside the MIN, this decision can be performed once for the whole duration of that VC connection, or it can be performed for every cell separately. With respect to routing information place, the routing information can either be transported by each cell itself via a so called routing tag, or it can be stored in routing tables in the basic switching elements which are composing the MIN. We apply cell by cell routing based on the output port address as the routing tag.

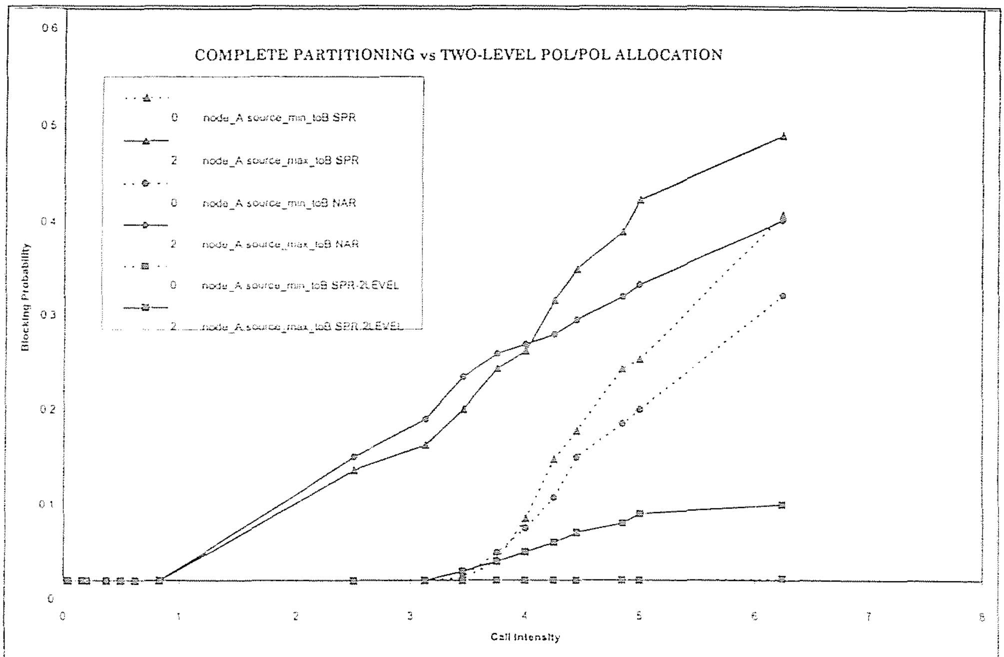


Fig. 10. CP vs 2-level POL/POL

In our simulation, the size of the MIN placed into the nodes of the network is determined by the number of VP links connected to the node in question. Since as described in Section 2 each node contains traffic sources, which generate traffic with user defined interarrival time and holding time and allow traffic generated by other nodes pass through the node (in case of multi-hop routes), the input ports of the MIN of a given node are grouped into two groups: (1) ports to which ATM cells come from nodes and (2) ports to which ATM cells come from traffic sources connected to this node (*Fig. 3 (a)*). Similarly, the output ports are grouped as (1) local sinks, i.e. cells destined to this node are routed to such ports, and (2) 'transit ports', i.e. cells belonging to connections which are destined to other nodes are routed to such nodes. *Fig. 3 (a)* shows the number of input and ouput ports of MIN placed into the 'A' node of the 5 node network and *Fig. 3 (b)* shows a 3-hop route from node 'A' to 'B'. We see that in our case the switch in node 'A' has 2×10 type-(1) input ports (these correspond to the 2×10 VP links connecting node 'A' to nodes 'B' and 'E') and 12 type-(2) input ports (these correspond to the 3×4 traffic sources placed into this node generating traffic belonging to 3 different service classes and 4 different destination nodes). Similarly, the node 'A' MIN has 2×10 type-(1) output ports and 12 type-(2) output ports.

Let's consider now a VC connection set up event at the call level. Suppose that a traffic source in node 'A' with bandwidth demand Bi has initiated a call from node 'A' to node 'B' and that the network level router has provided the 3 hop route: 'A'–'E'–'C'–'B'. Further, the link allocation algorithm has selected a VP link out of the 10 available at each of these hops, i.e. inside the transmission links 'A'–'E', 'E'–'C' and 'C'–'B'. The occurrence of this event at the call level was approved by the network, since at each transmission link along the route a VP link with sufficient capacity has been found and Bi capacity from each VP link capacity has now been allocated. When the VC connection is set up, the call level simulator places a connection identification number, the input port number (i.e. input VP link number) and the output port number (i.e. output VP link number) into the routing table of each switch along the given route. Obviously, the input/output port selection (i.e. the input/output VP link selection) at the cell level corresponds to the (VP) link allocation at the call level. As a given VP link becomes more and more saturated at the call level, it will mean a higher and higher intensity of arriving ATM cells into the switch of that node through that input port which is associated with that VP link. While this one-to-one association of VP links and switch input ports is a drastic simplification of the real situation, where this mapping is dynamic in time, it allows us to form a basic picture of the network behavior with respect to what impact the call level resource has on the cell level.

While this VC connection is 'alive', capacity will be allocated along the transmission path, and ATM cells will be flooding from the traffic source at 'A' via the switches 'A', 'E', 'C' and 'B' to the traffic sink at 'B'. While at the call level the capacity allocated along the path will be constant, the number of cells generated in a given time period will statistically fluctuate according to the burstiness characteristics of the source. A VC connection with bandwidth demand Bi at the call level corresponds to a certain *average* cell interarrival time at the cell level such that the bit stream will just be Bi [1], [24]. For instance if a VC connection with bandwidth demand $Bi = 1$ Mbit/s is established along the route, it will mean that traffic source will generate $10E + 06$ bits in a second *in average* during the holding time of that VC connection. (*Fig. 4*) [1].

Once the routing and link allocation (port) information has been communicated to the cell level, the cell level simulation runs independently and simultaneously with the call level part. The heart of the cell level simulation is the model of the switching element and the processing of the associated (ATM cell) arrival and departure events (*Fig. 5*).

Routing conflict occurs in a switching element when two cells coming from different incoming links are sent to the same outgoing link at the same or overlapped time interval (i.e. this model allows the switch to operate asynchronously, which from modelling point of view is more general than a synchronous model). When this occurs, an arbitration scheme is employed to serialize the access. In our simulation, however, the arrival of two different cells at two different input ports never occurs exactly at the same time (i.e. it happens with probability 0). Similar mapping of the operation of a switching element (even though not in a shared memory multiprocessor machine) can be found in [25], the detailed description of the implementation can be found in [30].

Altogether four types of events are modelled in the 2×2 switching element simulation. The first 2 event types, denoted by ARRIVAL[i], where i is 0/1 for the upper/lower input port, are the arrival events representing the processing of incoming cells from the upper and lower links, respectively. The last 2 event types, denoted by DEPARTURE[j], where j is 0/1 for the upper/lower outgoing link, are the departure events representing the forwarding of cells to the jth outgoing link. All events are stamped with an occurrence time. It is important to note that event execution must be performed in ascending order of occurrence time. Otherwise, incorrect simulation result will be produced [25]. The execution of an ARRIVAL event when the desired outgoing link status is idle results in a change of the link status to busy followed by the scheduling of a DEPARTURE event for the ARRIVAL. If the link status is already busy, however, the ARRIVAL event will only increment the queue length of the outgoing link. These operations mimic a real switch with output queuing [11], [12] where a cell is processed straightaway on its arrival or placed in the link buffer depending on the outgoing link status. As the ARRIVAL is no =longer outstanding after it is executed, scheduling the next ARRIVAL on the same link is necessary to prevent causality error [25]. Nonetheless, the immediate scheduling of the next ARRIVAL will be impossible if the cell queue is full, and in this case cell loss will occur. Similarly, the execution of the DEPARTURE event will have to schedule the next DEPARTURE event if there is (are) message(s) waiting to depart on the outgoing link. In addition to simulating a finite size buffer, a DEPARTURE event will also have to schedule an ARRIVAL to the link where a previous cell was blocked due to the unavailability of buffer space.

The main control to execute the events is iterative. It repeatedly selects an event with smallest occurrence time to execute. The execution of each event will update the system state, consisting of queue lengths, link status, number of arrivals and so on, and possibly schedule one or more event(s). The clock in the switching element advances together with occurrence time of the selected event. A version of the above switching element supporting internal backpressure [11] is discussed in detail in [25] and [30].

4. The Impact of Routing on Call Blocking

In this section, we try to evaluate the impact of routing algorithms on call blocking when combined with different link allocation strategies. We consider three different routing techniques: non-alternate routing (NAR), shortest path routing (SPR) and alternate routing (AR). NAR allows a single predefined route between any pair of nodes, AR defines a list of allowable routes, while SPR is dynamic in the sense that it searches for available routes in the network under run time. To each link, SPR assigns a weight defined as the reciprocal of the free capacity on that link. Thus, as VCCs are built up along the links and free capacity on the links decreases, the weight of these links quickly increases.

In *Figs. 6–8* we observe that all services perform worst under the NAR algorithm irrespective of the link allocation scheme applied when traffic load is tolerable by the network. This can be explained by the fact that NAR does not make use of possibly free VP links on alternate routes, but blocks the call if the predefined route is congested. However, if traffic load becomes high, NAR blockings are smaller than that of AR, and especially than SPR. This is because NAR always uses only one route to build up a VCC and thus behaves 'more greedy' with bandwidth than the two other algorithms, i.e. AR and SPR use more resources (links) in average to establish connections than NAR which clearly results in blockings of forthcoming calls, which have to be routed along one or several links of the already congested route.

We also note that SPR is clearly the best for all traffic classes under each link allocation scheme when the traffic load is tolerable by the network. Because of the weight function (reciprocal of free bandwidth), SPR spreads the incoming calls in the network, i.e. it eagerly seeks new routes instead of utilizing the already used but still not congested routes. It explains why this algorithm performs best under low load conditions. SPR obviously wastes more rapidly link capacity as traffic load becomes higher than the AR, which chooses a new route only when it has to, i.e. when the route of higher priority becomes congested. That is why we experience that as soon as the SPR starts blocking, it indicates that available resources have been consumed up and it rapidly goes up to the 'almost sure' blocking probability after a small further increase of the load.

The NAR actually can be further be subdivided into two different routing methods depending on the order in which the available VP links along the actual route are assigned to subsequent calls. If all calls are directed into the same VP link until there is enough capacity on that VP link, we talk about NAR with alternate VP link search. This is in contrast to NAR with shortest path VP link search, where similarly to the idea of SPR, the VP link of the smallest weight (within the given route) is chosen for subsequent calls. Thus, the VCCs belonging to subsequent calls will alternately choose the available VP links within the physical links. The effect of these two algorithms is not examined here, we note for the sake of accuracy that NAR results presented here were achieved with the second method (i.e. in the 'weighted search for VP links inside the transmission link' manner).

5. The Impact of Link Allocation on Call Blocking

Figs. 6–8 validate the well-known characteristics of the CS and CP allocation schemes [7]. The lack of link allocation policy, i.e. CS is unfair in the sense that it leads to heavy blocking of the broadband service class already at low traffic load conditions while allowing practically zero blocking to narrow band services. The need for traffic segregation has already been recognized, e.g. in [13], [14], [22] and algorithms to find the optimal partitioning in terms of VP link capacities with respect to VC connection set up probability and carried traffic are presented in these reports. These algorithms consist of defining an objective function, such as the carried traffic or route blocking and applying an optimization method with respect to this objective function assuming the CP policy. The optimization algorithm relies on approximations like Erlang's B formula or the Knapsack or the Gaussian approximation [21], [22]. A method based on minimizing the entropy function is proposed by [19]. This 'push down' algorithm dimensions the Virtual Paths based on Chernoff Bound. It derives an entropy measure – instead of blocking measure – that is to be maximized for each VP within the available physical capacity in order to balance the blocking probability of the offered calls on the physical links. Under this scheme (CP) the wide band service class' performance is improved at the expense of introducing blocking to narrow band service classes (*Figs. 6–8*). Note that this observation is valid only for medium and high traffic loads; for low load the CP results in even higher blocking probability than in the CS case. This can be explained by the low link utilization of the available capacity at low loads: the CP rule restricts all service classes to their 'own' VP links and leaves other VP links under-utilized when capacity is there – possibly – available. At higher loads, however, the CP successfully protects the broadband classes from the attacks of the intensive narrow band classes. The important conclusion here is that CP cannot be merely based on the offered load: service classes with identical offered load but differing intensity and bandwidth demand suffer significantly different blocking probabilities in case of equal partitioning. To conclude we find that the CS policy is adequate when traffic is tolerable by the network, while traffic segregation is beneficial at medium and especially at high loads.

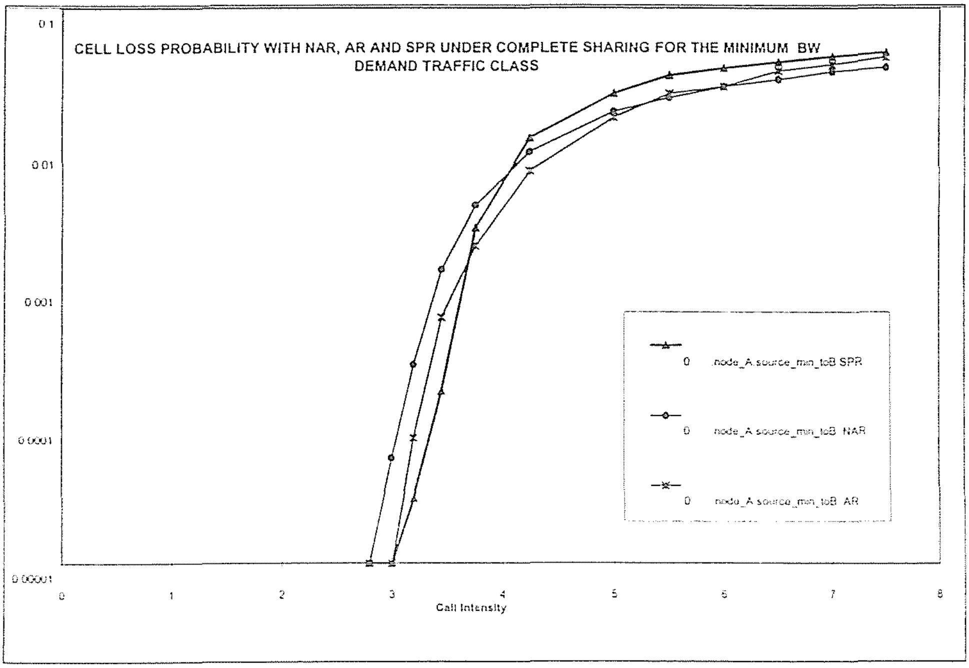


Fig. 11. Cell loss probability for different routing strategies

To combine the advantages of the CP and CS policies and to achieve fair distribution of blocking independent of the offered load we now apply the partial overlap (POL) allocation rule. First based on the previous experiments' results, we assess the POL boundaries heuristically, and then we propose an algorithm to determine the POL boundaries (*Fig. 1*). To assess the gain produced by this POL optimization algorithm *Fig. 8(a)* shows the broadband and narrow band service classes when applying NAR and SPR.

Concerning the heuristic approach we note that the POL policy provides for a more efficient allocation of available bandwidth than the CS/CP rules (*Fig. 8(a)*). This improvement is most impressive under low load values, and practically vanishes as the network becomes congested. The interesting phenomenon here is that the narrow band service class is not seriously affected by the fact that the broadband service class is multiplexed into its links. The medium service class, in contrast, suffers a notably higher blocking compared with the CP case.

The above observations combined with results in [19] lead us to the following link allocation rule applicable to integrated services networks. Since when mixing services with different bandwidth demands and offered traffic such that the offered loads are equal the narrow band service class gets almost exclusive access to the shared link's capacity, the narrow band service class access should be limited to common resources. Since optimal CP algorithms are available, the following algorithm is now feasible:

(1) Partition the physical network optimally using the CP algorithm in [19]. This optimization results as many VP links $(1 \ldots N)$ in each physical link as there are service classes, each with a well-defined Ci capacity ($i = 1 \ldots N$, where N is the number of service classes).
(2) Number the service classes from $1 \ldots N$ such that their respective bandwidth requirements are in increasing order $Bi < Bj$ if $i < j$. Then let service class i get VP links $1 \ldots i$.

The exact realization of this resource assignment requires that the number of VP links and their capacities be redefined in our network under study, since the partitioning algorithm results in continuous VP link capacities. However, in order to assess the performance of the above POL partitioning, we approximate the result with the available VP links with integer multiples of discrete capacities (i.e. 150 Mbit/s), even if the FSP would readily allow changes in the VP link capacities.

As an illustration of the above simple algorithm, consider the result of the POL policy in *Fig. 8(b)*. In our example network the POL configuration will become such that service class 1 gets links 1–2, service class 2 gets links 1–6 and service class 3 is allowed to use all links (*Fig. 1*). From the broadband service class viewpoint the dedicated links (7–10) guarantee its performance under heavy traffic load and can take advantage of the additional shared links under low and medium load.

6. Two Level Link Allocation Schemes

All the above link allocation rules lead to bandwidth waste at least in those VP links that are dedicated to the broadband service class. In fact, all VP links will waste bandwidth at least to the extent that is determined by the narrowest service class multiplexed into that link. For instance, in our example 150 Mbit/s links dedicated to the 120 Mbit/s service class will surely waste 30 Mbit/s irrespective of the routing algorithm. To improve VP link utilization we propose the 2-level link allocation rule. In this scheme the higher level rule determines which service class(es) is allowed to utilize which VP links, and the low level rule determines to which extent (i.e. how big portion of) the shared VP links can be used by the service classes sharing that VP link. The introduction of this level gives rise to a number of possible arrangements of the service classes between the available resources (*Fig. 9*). For instance, the CS/POL allocation rule applies CS at the higher level just as it is described above, but inside the individual VP links, say 120 Mbit/s is reserved for service class 3, the remaining 30 Mbit/s bandwidth is available to service classes 1 and 2. What we expect from introducing this second level of allocation rule is that it accommodates itself more flexibly to the fine granularity bandwidth demands inherent to services in B-ISDN networks. Similarly, the POL/POL allocation uses the POL scheme at both levels.

Optimization of the network configuration in terms of blocking probability and carried traffic under this rule is more complex than optimization at the single level. As an illustration of the performance improvement stemming from this rule, let's consider the POL/POL case (*Fig. 9*) in *Fig. 10*. It shows the performance of the narrow band and broadband service classes under the CP and under the POL/POL policy when using SPR. All service classes drastically decrease call blocking probability because of the much higher VP link utilization: especially the broadband and narrowest band service class benefit from the improvement both for low and high load values.

7. The Impact of Routing on Quality of Service (QoS) Parameters

In this section, we try to evaluate the impact of routing algorithms on cell loss. We apply the SPR, AR and NAR between the traffic sources at node 'A' and the traffic sinks at node 'B'. Regarding VP link allocation we focus on the CS method, to study the effect of other VP link allocation methods is the subject of our future research. (Currently we are continuing our extensive survey of resource allocation strategies and evaluating them with respect to cell loss, cell delay and cell delay variation.)

Fig. 11 shows the end-to-end cell loss probability between nodes 'A' and 'B'. We see that even at the cell level the call level resource allocation plays a significant role: one and the same network (with fixed buffer size switches) will impose different cell loss probability on the cell streams flooding through the switches between source and destination. Again we find that when traffic is tolerable by the network SPR causes the least cell loss. We explain this phenomenon by the fact that SPR spreads the incoming calls in the network, i.e. it eagerly seeks new routes instead of utilizing the already used but still not congested routes. From the switches point of view, this results in utilizing all the buffers in the network. In contrast, NAR does not make use of 'idle' buffer capacities in alternate routes switches, but begins to drop cells. However, SPR obviously wastes more rapidly link and buffer capacity as traffic load becomes higher than the AR, which chooses a new route only when it has to, i.e. when the route of higher priority becomes congested. That is why experience that as soon as the SPR starts loosing cells, it indicates that available resources have been consumed up and it rapidly goes up to high blocking (loss) probabilities after a small further increase of load.

8. Conclusions and Future Research

Two aspects of resource allocation at the call and the cell levels have been studied: routing and VP link allocation. We have found that at both levels SPR performs best under realistic offered load values, while NAR is better during congested periods. Regarding capacity allocation along the VP links, we have found that the offered load alone is not sufficient to select the optimal policy; calls with the same offered load values can suffer significantly different call blocking probabilities when they share link capacities, or when capacity is equally partitioned among them. Therefore partial overlap allocation schemes seem to perform better under any load conditions, and a proposed two-level link allocation algorithm, as a refinement, is promising. Optimizing the two-level link allocation scheme is the topic of our future research. We intend to develop call level algorithms that take into account the impact of the call level resource allocation strategies on the cell level. Different switch architectures and more elaborate models of these need to be investigated. It is still an open question exactly what combination of the above (and possibly other like load sharing and trunk reservation) strategies perform best in terms of cell loss, cell delay and cell delay variation. The briefly described simulation software, which supports both call and cell level performance analysis of resource allocation algorithms, however, promises to be helpful in this research.

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